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Predicted hue and saturation for non-spectral lights

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Predicted hue and saturation for non-spectral lights

Kulp, Thomas David, Ph.D.

University of New Hampshire, 1993

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PREDICTED HUE AND SATURATION
FOR NON-SPECTRAL LIGHTS

BY

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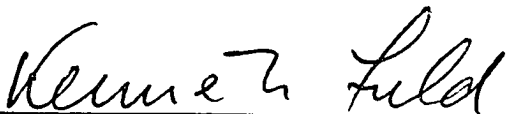
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Submitted to the University of New Hampshire
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in
Psychology

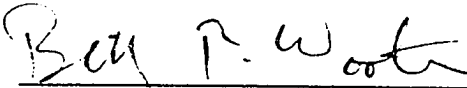
December, 1993

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ABSTRACT

PREDICTED HUE AND SATURATION FOR NON-SPECTRAL LIGHTS

by

Thomas D. Kulp
University of New Hampshire, December, 1993

The Jameson and Hurvich opponent colors model of hue and saturation was tested for spectral and non-spectral lights. Four observers scaled, using standard color naming techniques, the hue and saturation of both spectral and non-spectral lights. These lights consisted of 11 wavelengths from 440 to 640nm in steps of 20nm and consisted of 5 purities, 1.0, 0.80, 0.60, 0.40 and 0.20. Admixtures of monochromatic light and a xenon-white desaturant yielded the different colorimetric purities. For each observer, chromatic response functions were measured by the method of hue cancellation for each purity, and an achromatic response function was measured by the method of heterochromatic flicker photometry for spectral lights. Chromatic response functions measured for a particular purity and the achromatic response function were used to predict hue and saturation for that purity. Hue varied with purity, the Abney effect, consistent with what would be expected due to additivity and opponent cancellation if the xenon-white desaturant were yellowish. The model made approximate predictions of hue for each purity, but

failed to predict precisely the Abney effect. Previous results of a minimum forming on the saturation function at 480nm with decreasing purity were confirmed. This minimum was possibly due to opponent cancellation between the yellowish xenon-white and the predominately blue appearing 480nm light. An additional experiment demonstrated that the xenon-white appeared yellowish. The model made relatively poor predictions of saturation, tending to overestimate short-wave lights and underestimate long-wave lights. The possibility of the rods contributing to saturation was discussed. An additional experiment found that stimulus parameters that favor rod contribution weaken the model's predictions of saturation, while stimulus parameters that do not favor rod contribution improve the model's predictions of saturation.

I. INTRODUCTION

Although light is the physical stimulus for color vision, color appearance depends on the receptors in the eye that convert the light into a neural signal and on the subsequent neural processing by the eye and brain. According to modern opponent-colors theory (Hurvich and Jameson, 1957; Ingling and Tsou, 1977; Guth, Massof and Benzsshawel, 1980) there are three types of receptors that are linked in various ways to three neural channels. The relative amounts of activity in the three neural channels account for the hue and saturation of colored lights.

Models of color appearance are important for color specification, because they predict what colored lights look like (Gordon and Abramov, 1988). Does the light appear yellow, blue, red or green or some mixture of these hues? Is the light a vivid or a pale hue?

Color appearance is typically characterized by the three psychological dimensions of hue, saturation and brightness. The physical dimensions of light--wavelength, purity and intensity--are correlated with the psychological dimensions.

The psychological dimension of hue depends not only on wavelength but also on purity. Adding increasing amounts of a white appearing light to a particular wavelength of light causes the mixture to change in hue as well as in saturation. This change in hue by addition of white light

is known as the Abney effect (Abney, 1910; Ayama, Nakatsue and Kaiser, 1987; Burns, Elsner, Pokorney and Smith, 1984; Ikeda and Uehira, 1989; Kurtenbach, Sternheim and Spillmann, 1984). Hue also depends on intensity, which is known as the Bezold-Brucke effect (Purdy, 1931a).

The psychological dimension of saturation depends on the physical dimension of purity. Intermixing increasing amounts of white light with a pure spectral light (while holding dominant wavelength and intensity constant) results in a light appearing increasingly less saturated. Thus, the saturation of lights decreases with decreasing purity (Indow and Stevens, 1966; Onley, Klingberg, Dainoff and Rollman, 1963; Uchikawa, Uchikawa and Kaiser, 1984). The saturation of lights also varies as a function of wavelength (Fuld, 1991; Gordon and Abramov, 1988; Jacobs, 1967; Jameson and Hurvich, 1959; Jones and Lowry, 1926; Kaiser, Comerford and Bodinger, 1976; Priest and Brickwedde, 1938; Purdy, 1931b). The middle of the spectrum appears less saturated than the ends. Saturation also depends on intensity (Hurvich and Jameson, 1955; Kimura, 1991).

The CIE defines the saturation of a light as the perceived proportion of chromaticity (or hue) to total sensation (Hunt, 1977). A highly saturated light is perceived as vivid in hue, appearing to have a large chromatic (hue) component and a small achromatic (white, black or gray) component, while a less saturated light is perceived as pale in hue, appearing to have a small chromatic component

and a large achromatic component.

Researchers have measured saturation by, among other methods, the direct psychophysical scaling technique of saturation estimation (Fuld, 1991; Gordon and Abramov, 1988; Jacobs, 1967; Jameson and Hurvich, 1959; Kaiser, Comerford and Bodinger, 1976; Uchikawa, Uchikawa and Kaiser, 1984). Saturation estimation requires observers to rate the perceived hue content of a light in relation to the total hue and whiteness content. For instance, an observer rates a light appearing pure in hue as 100%, a light appearing pure white as 0%, and lights of varying proportions of hue and whiteness as numbers between 0 and 100%.

Non-spectral lights can be specified within the CIE 1931 (x,y) chromaticity diagram in terms of excitation purity and dominant wavelength or can be specified by colorimetric purity, the ratio of the luminance of the spectral light to the luminance of the spectral light plus the luminance of a white light. Both excitation purity and colorimetric purity vary from zero, the white light alone, to one, the spectral light alone.

The purpose of the present study was to see how well the opponent-colors theory, as detailed by Hurvich and Jameson (1957), predicts hue and saturation based on variations of wavelength and purity.

According to modern opponent-process models of color vision (e.g. Hurvich and Jameson, 1957; Ingling and Tsou,

1977; Guth et al., 1980) there are three neural systems: two chromatic (a red-green and a yellow-blue) and one achromatic (white-black). The chromatic channels are opponent in nature. Opponent hues are antagonistic in that they cannot be seen both co-temporally and co-spatially. Red is opponent to green and yellow is opponent to blue. Each chromatic opponent channel can signal only one of these elemental sensations at a time; the red-green channel can signal either red or green but not both simultaneously, and the yellow-blue channel can signal either yellow or blue but not both simultaneously. As a result of this opponent coding of hue, lights cannot appear yellowish-blue, bluish-yellow, reddish-green or greenish-red. If lights that elicit opponent sensations are admixed in the right proportion the sensations cancel each other. For instance an additive mixture of a red appearing light and a green appearing light may appear predominantly red or predominantly green or neither red nor green, depending on the relative proportions of the lights, but will never appear red and green simultaneously. The same holds for mixing yellow and blue lights. According to opponent-colors theory, hues of the spectrum can thus appear red, green, yellow and blue and paired combinations of these hues except for red-greens and yellow-blues.

Hurvich and Jameson (1955) quantified opponent-colors theory by psychophysically measuring the spectral responsivity of the red-green and the yellow-blue channels.

Each wavelength of light throughout the spectrum evokes a certain amount of either red or green response and a certain amount of either yellow or blue response, and the relative responsivity or activity in each of these channels for wavelengths throughout the spectrum is represented by the chromatic response (or valence) function.

Chromatic response functions are typically measured by the method of hue-cancellation (Jameson and Hurvich, 1955). The measure of chromatic response to a light of a given wavelength is obtained by determining how much of a light that elicits the opponent or antagonistic response is necessary to zero or null the channel to equilibrium position. For instance, to determine the blue response for a particular wavelength of light that appears blue, increasing amounts of yellow light are added to this blue appearing light until the light appears neither blue nor yellow. The intensity of the yellow light needed to cancel the blue is taken as a measure of the amount of blue activity in the yellow-blue channel at that wavelength. The same yellow light can then be used to cancel blue in all blue appearing lights throughout the spectrum, and the relative amounts of the yellow light necessary to cancel blue is taken as a measure of blue responsivity. This procedure is followed for measuring yellow responsivity by using a blue canceling light, for measuring red responsivity by using a green canceling light, and for measuring green responsivity by using a red canceling light.

The achromatic response, the response of the white-black channel cannot be determined in the same manner, since white and black are not opponent in the same sense (Quinn, Wooten and Ludman, 1985). The achromatic channel's spectral responsivity has been represented by most opponent-color vision models by the standardized function V_λ (the CIE photopic luminosity) function. The implied whiteness response is represented by V_λ and the blackness response is represented by the inverse of V_λ (Volbrecht, Werner and Cicerone, 1990). Curves shaped like V_λ can be measured psychophysically by heterochromatic flicker photometry (HFP). HFP is not based on direct perceptual judgments of whiteness or blackness but is used as a measure of the relative response of the white-black channel to spectral lights.

Other researchers (Ejima and Takahashi, 1984; Fuld, 1991; Romeskie, 1978; Takahashi and Ejima, 1984; Takahashi, Ejima and Akita, 1985; Werner and Wooten, 1979) have measured chromatic response by Jameson and Hurvich's hue-cancellation technique and have obtained similar functions. As noted by Ayama, Kaiser and Nakatsue (1985), there are differences in the shapes of the functions between observers even within the same study.

What is the relationship between chromatic and achromatic response functions and the appearance of spectral lights? If the appearance of hue is directly related to the relative responses of the chromatic-channels, does this then mean

that an observer's chromatic response function will predict that observer's perceived hue? Hurvich and Jameson (1955) related opponent responsivity to the hue of spectral lights. The ratio of one particular chromatic response to the sum of all the chromatic responses at a given wavelength is called a hue coefficient:

$$H(r,g)_\lambda = \frac{(|r-g|)_\lambda}{(|r-g| + |y-b|)_\lambda} \quad (1)$$

$$H(y,b)_\lambda = \frac{(|y-b|)_\lambda}{(|r-g| + |y-b|)_\lambda} \quad (2)$$

where $H(r,g)$ and $H(y,b)$ are hue coefficients which predict the percentage of red or green and of yellow or blue for a particular light, and $r-g$ and $y-b$ are the values of red-green and yellow-blue responsivity, respectively. They hypothesized that the hue coefficient provided a direct description of the hue appearance of the spectrum. Werner and Wooten (1979) tested this hypothesis by having observers estimate the percentages of the elemental hues red, green, yellow and blue in spectral lights. They also measured individual chromatic response functions. They found that the hue coefficient calculated from the individual's chromatic response function was predictive of hue estimation for that individual. The implication is that hue is coded by a relatively simple underlying process, that of two opponent channels. Although Werner and Wooten have shown

the hue coefficient to relate chromatic response to hue for spectral lights, no study has tested the hypothesis that the hue coefficient is predictive of hue for different purities.

Jameson and Hurvich (1955) also predicted saturation for spectral lights based on the chromatic and achromatic response functions. They hypothesized that the saturation of a light depends on the ratio of the total chromatic response to the total chromatic response plus the achromatic response. They termed this ratio the saturation coefficient. At the two spectral extremes where the chromatic responses are large relative to achromatic response, the saturation is predicted to be high. In the middle of the spectrum where chromatic response is low relative to the achromatic response, spectral saturation is predicted to be low.

The saturation of spectral lights, which have a purity of 1.0, is measured by a number of different methods which are reviewed by Kaiser, Comerford and Bodinger (1976). The method of saturation estimation requires observers to rate lights in terms of the proportion of hue seen relative to hue and whiteness combined. Researchers using this method have found similar functions showing the middle of the spectrum to be less saturated than the ends (Boynton, Schafer and Neun, 1964; Fuld, 1991; Gordon and Abramov, 1977; Gordon and Abramov, 1988; Jacobs, 1967; Jameson and Hurvich, 1959; Kaiser, Comerford and Bodinger, 1976;

Uchikawa, Uchikawa and Kaiser, 1984).

Fuld (1991) tested the hypothesis that the saturation of spectral lights could be predicted by the saturation coefficient. For individual observers he measured chromatic and achromatic response functions and then measured saturation of the spectrum by the method of saturation estimation. He found that the saturation coefficient predicted saturation estimation, except for a very small but consistent difference of short-wavelength lights appearing less saturated than predicted and long-wavelength lights appearing more saturated than predicted.

To account for the difference between obtained and predicted results, Fuld (1991) revised the saturation model, which he refers to as the linear valence model, by adding two weighting factors to the model: one for a nonlinear yellow-blue response and the other a desaturating signal from the rods. An improved fit between predicted and obtained saturation was obtained. Fuld hypothesized that the mismatch between predicted and obtained saturation is due to the model not taking into account a contribution to saturation by the rods. He reasoned that if rods contribute to saturation, then spatial and temporal properties of the stimulus that minimize the effects of rod contribution should improve the model's predictions.

The above studies measured the saturation of spectral lights, but did not address the saturation of non-spectral lights. Onley, Klingberg, Dainoff and Rollman (1963) and

Indow and Stevens (1966) obtained magnitude estimates of saturation for lights of fixed wavelength and varying purity. They found that a power function represented the relation of increasing saturation with increasing purity for each wavelength and that the exponent of the power function was different for each wavelength they studied. Testing a greater range of lights of varying wavelength and purity, Uchikawa et al. (1984) had observers estimate saturation. Saturation estimates increased with increasing purity for all wavelengths, but the rate of increase varied according to wavelength. The results of these studies imply that the shape of the saturation function changes as a function of purity.

A replot of the Uchikawa et al. (1984) data by the present author, shown in Figure 1, shows how the saturation function varies as a function of purity. Saturation estimate is plotted as a function of wavelength for different levels of purity from 1.0 to 0.1. At a purity of 1.0 the shape of the saturation function is similar to the results of previous studies estimating saturation of spectral lights, but with a decrease in purity the shape of the function changes: it becomes flatter, and a new minimum forms at about 470nm.

Can the changes in the shape of the saturation function as a function of purity be explained within the Jameson and Hurvich (1955) model? More specifically, do the relative responses of the chromatic and achromatic channels

change as a function of purity in a way that predict the changes in saturation as a function of purity?

Predictions of saturation for varying purity require that the chromatic and achromatic response functions be applied to additive mixtures of lights, since a white light is added to spectral lights in order to vary purity. The Jameson and Hurvich model assumes that their chromatic response functions are linear with additive mixture of lights, given that the overall light level remains relatively constant. Linearity with mixture refers to the total chromatic response of a mixture of lights being equal to the sum of the chromatic responses of the component lights weighted by their relative energy within the mixture. According to strict linearity, chromatic response measured for a wavelength of light at one level of intensity and purity should be linearly related to response for that light at other levels of intensity and purity. Linearity simplifies matters by making it unnecessary to measure chromatic response for all levels of intensity and purity in order to specify fully chromatic response for all lights. In fact, Jameson and Hurvich presented their response functions for an equal energy spectrum which is valid only if the function is independent of intensity level measured. Also, their response function is supposed to be independent of choice of canceling stimulus which requires that linearity with additive mixture hold.

Krantz (1975) in applying measurement theory to color

vision stated two axioms necessary for the assumption of linearity to hold for hue-cancellation. The hue-cancellation function is based on observations of sets of red-green equilibrium lights, lights that appear neither red nor green and observations of yellow-blue equilibrium lights, lights that appear neither yellow nor blue. Axiom one states that red-green and yellow-blue equilibrium lights remain at equilibrium under changes of intensity. Axiom two states that equilibrium lights remain in equilibrium with additive mixture. That is, varying proportions of mixtures of either red-green or yellow-blue equilibrium lights remain in equilibrium. Also, desaturating a red-green or a yellow-blue equilibrium light with a white light results in a light that remains in equilibrium. Axiom one is related to the Bezold-Brucke effect (Purdy, 1931a), which refers to the change in hue with varying intensity, and axiom two is related to the Abney effect, which refers to the change in hue with varying purity. According to Krantz, the Bezold-Brucke effect and the Abney effect should not be observable for equilibrium lights if linearity holds for hue cancellation.

Are achromatic and chromatic responsivity linear functions of both intensity and purity? Achromatic response (as measured by HFP) obeys the additivity law and is generally thought to be linear with light mixture (Guth, Donley and Marrocco, 1969; Kaiser and Wyszecki, 1978). Studies that have explored chromatic response as a function

of intensity have found nonlinear changes in chromatic responsivity as a function of intensity. Researchers have found violations of Krantz's first axiom for yellow-blue and red-green equilibrium lights (Ejima and Takahashi, 1984 and 1985; Elzinga and de Weert, 1984; Ikeda and Ayama, 1980; Ikeda and Ayama, 1985; Ikeda, Ayama and Ohmi, 1982; Larimer, Krantz and Cicerone, 1974 and 1975; Raaijmakers and de Weert, 1975).

The Jameson and Hurvich model predicts changes in chromatic responsivity with intensity. Their model is in accord with the classic Bezold-Brucke effect by postulating that yellow-blue response increases at a faster rate than red-green response with increasing intensity.

For a constant intensity, chromatic response as a function of purity is predicted by the Jameson and Hurvich model to be linear (Hurvich, 1981; Hurvich and Jameson, 1956; Krantz, 1975). Although chromatic response decreases with decreasing purity, the hue coefficient for each wavelength does not change. Since the hue coefficient remains constant, one would predict a light of a particular wavelength to appear constant in hue but different in saturation with varying purity. The Abney effect demonstrates the failure of this linearity assumption (Ayama, Nakatsue and Kaiser, 1987; Burns, Elsner, Pokorney and Smith, 1984; Ikeda and Uehira, 1989; Kurtenbach, Sternheim and Spillmann, 1984). With the addition of a perceptually neutral white as a desaturant, blue and

red-blue appearing wavelengths increase in redness, yellow-green appearing wavelengths increase in greenness and blue-green and yellow appearing wavelengths remain relatively constant in hue. Individual differences are found for red-yellow lights-- for some individuals the lights become redder and for other individuals the lights become yellower. These changes in hue tend to increase with decreasing purity (Kurtenbach et al. 1984).

Given the results of the above studies, chromatic response is not likely to be linear with purity, and consequently the chromatic response function measured at a purity of 1.0 will probably not predict hue and saturation for other purities. However, measurements of chromatic response at a particular level of purity may predict hue and saturation for that purity level.

No previous studies have tested the Jameson and Hurvich model of hue and saturation for non-spectral lights. Since there are individual differences in chromatic and achromatic response functions, as well as in saturation and hue estimates, a test of the model requires that predictions of hue and saturation for an individual be made on the basis of that individual's chromatic and achromatic response functions.

In the present study, chromatic response functions measured for a particular purity and an achromatic response function were used to predict hue and saturation for that purity. Five levels of purity were tested. The achromatic

response functions were measured for spectral lights and were used to predict saturation at all levels of purity. The hue coefficient should predict hue and should be in accord with the Abney effect. The saturation coefficient should predict saturation and should account for the change in the shape of the saturation function with varying purity as shown by Uchikawa et al. (1984).

II. METHODS

Subjects

Four subjects participated in the experiments. All subjects were tested for normal color vision on the basis of the Farnsworth Dichotomous Panel D-15 test and the Ishihara Pseudoisochromatic test.

Apparatus

The stimuli were presented foveally in a standard four-channel Maxwellian-view optical system with a 1,000 W Xenon-arc lamp (see Figure 2 for a diagram). The light of each channel passed through a water filter (WF1, WF2, WF3 and WF4) in order to reduce infrared energy. Monochromatic light was produced in Channel I by a monochrometer (M) and in Channel IV by interference filters (I4). Channels II and III produced xenon-white light. The intensity of the light in each channel was varied with neutral-density filters (F1, F2, F3 and F4) and neutral-density wedges (W1, W2, W3 and W4). Channels II and IV provided the test stimuli, while Channel I provided the cancelling stimuli, for hue cancellation. Channel I and Channel III were temporally alternated by a rotating sectored mirror (RM) for use in flicker photometry. The temporal presentation of the stimuli was controlled with a high-speed electromechanical shutter (SH). The stimuli were defined by a circular field (CF). Chromatic aberration

was controlled with an achromatizing lens (AL). An adjustable dental-impression bite bar and head rest assembly stabilized the observer's head. The experimenter viewed the observer's pupil through an auxiliary channel (AC) so that the observer's pupil could be aligned with respect to the optical axis.

Stimuli

Fifty-five lights of different wavelength and purity were presented to the observers. These lights consisted of 11 wavelengths from 440 to 640 nm in steps of 20 nm and consisted of 5 purities, 1.0, 0.8, 0.6, 0.4 and 0.2, for each wavelength. Purity is defined as colorimetric purity (Cp):

$$Cp = \frac{L_{\lambda}}{L_{\lambda} + L_w} \quad (3)$$

where L_{λ} refers to the Troland value of monochromatic light and L_w refers to the Troland value of a xenon-white field. The admixtures, yielding colorimetric purities of 0.80, 0.60, 0.40 and 0.20 were maintained at a constant Troland value of 100.

All test stimuli consisted of a 1 deg circular field with no background and were flashed for 1 second every 5 seconds. Stray light passing through the final lens provided a very dim 19 deg circular fixation field.

Calibrations

A United Detector Technology Model 61

radiometer/photometer was used to measure the optical densities of all neutral-density wedges and filters for every 50nm, and was used to make daily measurements of the relative spectral energy for the appropriate channels and wavelengths. Retinal illuminance was measured with a Litemate/Spotmate System 500 photometer according to the procedure described by Westheimer (1966).

Procedure

The method of hue cancellation was used to measure chromatic responsivity at each level of purity for each observer (Jameson and Hurvich, 1955). Four experiments were required for completely determining the chromatic response function at each purity level. First, each subject's unique hues were determined for use as canceling stimuli. Second, yellow, blue, red and green chromatic valence curves were measured by opponent cancellation. This experiment determined only the shapes of the four curves. A third and a fourth experiment determined the relative heights of the four curves, which represent the relative strengths within and between the two opponent systems. In another experiment, HFP was used to determine achromatic response, and in a sixth experiment, saturation estimation was used to measure saturation.

All experimental sessions began following 10 minutes of dark adaptation. Alignment of the center of the subject's pupil with respect to the axis of the optical system was maintained throughout the experiment.

Experiment One: Unique Hue Determination

Unique hues determined for a purity of 1.0 were used as the canceling stimuli for each level of purity. Unique yellow, blue and green hues were determined. Unique red was not determined since it is not present in the spectrum. A predominately red appearing 640nm light was used as the red canceling stimulus.

The method of constant stimuli was used for presenting the stimuli for determining unique hues. The observer was presented with a range of lights, varying every 2nm in wavelength and set to a Troland value of 100. Pilot data determined the approximate wavelength and range of uncertainty for each unique hue. Each light within the range was presented once in a random order for a particular trial. There were two trials per day over three days for a total of six trials. The observer was forced to make a binary judgment about the hue of each light. When determining unique blue and yellow the observer judged the lights to appear either reddish or greenish. When determining unique green the observer judged the lights to appear either yellowish or bluish. From the psychometric function of percentage response ("red" or "yellow") verses wavelength, the 50 percent point was taken as the wavelength of the unique hue.

Experiment Two: Chromatic Valence Curves

The blue canceling stimulus was used to cancel yellow in all yellow appearing lights; the yellow canceling

stimulus was used to cancel the blue in all blue appearing lights; the red canceling stimulus was used to cancel the green in all green appearing lights; and the green canceling stimulus was used to cancel red in all red appearing lights. The canceling stimulus and the appropriate test stimulus were superposed within a circular field subtending 1 deg, and they were exposed for 1 second every 5 seconds. The observer adjusted the radiance of the canceling stimulus until the test field was at an opponent equilibrium. For instance, for yellow appearing test stimuli and a blue canceling stimulus, the subject was instructed to adjust the blue canceling stimulus, by both increasing and decreasing its intensity, until the test field appeared neither yellow nor blue.

Red, green, yellow and blue chromatic valence curves were measured at each level of purity. One chromatic valence curve was measured at a time with the test stimuli presented in a random order. Test stimuli of one purity level were presented during a session. Purity level was presented in a random order across sessions. After one practice session, results for each test stimulus was based on four trials across two days.

Experiment Three: Cancellation of Canceling Stimuli

The relative height of the yellow to the blue curve and of the red to the green curve was determined by the relative proportions of the canceling stimuli necessary for either yellow-blue and red-green equilibrium,

respectively. The canceling stimuli were mixed in varying proportions at 5 troland intervals while keeping their total troland value constant at 100 trolands. These lights were presented to the observer in a random order by the method of constant stimuli. The observer judged the mixture as appearing either yellow or blue, or red or green. The observer made six judgments across three days. From the psychometric function of percentage response ("yellow" or "red") verses mixture proportion, the 50 percent point was taken as the proportion of the two canceling stimuli necessary for opponent equilibrium. The two curves were adjusted according to the inverse of the relative energies of the canceling stimuli at equilibrium.

Experiment Four: Hue Naming

The height of the yellow-blue curve relative to the red-green curve was adjusted according to each subject's perception of hue at each level of purity. The method of hue naming was used. The percentage of red, green, yellow and blue was estimated for each of the test stimuli with the constraint that the total must add to 100 percent. The subjects made three judgments of hue for each of the test stimuli across three days. Each day the subject viewed all purity levels one purity level at a time. Both purity level and test stimuli within a purity level were presented in a random order. The relative height of the red-green to the yellow-blue curve was adjusted in order to minimize the sum of the squared deviations between hue coefficients

computed from the chromatic response curves and the results of hue naming.

Experiment Five: Achromatic Response

Heterochromatic flicker photometry (HFP) was the measure of achromatic response. The observer performed HFP between the monochromatic test stimuli of a purity of 1.0 and a xenonwhite field set to 100td. The test stimulus and the white light were superposed on a 1 deg circular field and were presented in counterphase at 20 HZ. The observer adjusted the radiance of the monochromatic light to achieve a criterion of minimum flicker between the two fields. Four trials were performed for each wavelength.

Experiment Six: Saturation Estimation

The observers estimated the percentage of whiteness relative to total color (chromatic plus achromatic component) for each of the test stimuli. Saturation (the percent hue content of the light) was defined as 100 percent minus the percentage estimate of whiteness. The subjects made three judgments for each of the test stimuli across three days. Each day the subject viewed all purity levels one purity level at a time. Both purity level and test stimuli within a purity level were presented in a random order.

III. RESULTS

Unique Hue Determination

Unique hues for each subject are listed in Table 1. The unique hues were determined from each observer's 6 responses using the SAS/GRAPH spline interpolation option SM (SAS/GRAPH, 1985): a smooth line, not necessarily including the points, was drawn through the points on a graph of wavelength verses percent response. A vertical line was then drawn to intersect the curve at the 50 percent point of the psychometric function. The range for each unique hue, listed in Table 1, is a range of the unique hue computed for each of the three days. The unique hue results, except for DM's unique green, which is a longer wavelength than normal and is highly variable, are within the range of previous studies which measured unique hues under similar conditions (see Ayama et al, 1987).

Chromatic Response

Figures 3 through 6 are chromatic response functions measured for different purities for subjects JH, RS, RH and DM, respectively. Blue and green functions are arbitrarily assigned negative values and red and yellow functions are arbitrarily assigned positive values to reflect the antagonism within an opponent system. The relative heights of the yellow to the blue curve and of the red to the green curve are adjusted according to

Experiment 3. The relative magnitudes of the yellow-blue curve to the red-green curve are adjusted using the hue naming data of Experiment 4. A computer program was written to adjust the relative magnitude of the yellow-blue curve to the red-green curve in order to achieve a least squares fit between hue coefficients computed from the chromatic response functions and the hue naming data.

The range of chromatic response was computed for each test stimulus across the two days of testing. The mean range computed for each curve ranged from 0.09 for the blue curve to 0.34 for the yellow curve for JH, from 0.07 for the yellow curve to 0.22 for the green curve for RS, from 0.39 for the short-wave red curve to 2.01 for the blue curve for RH and from 0.01 for the long-wave red curve to 0.83 for the yellow curve for DM. There was no pattern of certain curves being more variable between observers.

Generally, each of the test stimuli appeared the same two hues across all of the trials of hue cancellation (Experiment 2) and hue naming (Experiment 3). These two hue names are listed under the heading of hue in Tables 2 to 5. In cases where the observer used a different hue name in at least one of the trials, the variable hue names are listed after the dash. For example, in Table 2 the 480nm light appeared blue-green at purities of 1.0 to 0.60, but at purities of 0.40 and 0.20 appeared blue-green on some trials and blue-red on other trials. The appearance of a test stimulus on a majority of trials was used for

assigning the results for that test stimulus to either the yellow or the blue curve and to either the red or the green curve.

In Figures 3 through 6 the shapes of the chromatic response functions for a purity of 1.0 are not identical between observers as seen by differences in the wavelength of maximum response. The mean wavelengths of maximum response (and standard deviations in parentheses) are located at 443nm(5) and 615nm(10) for the red curve, 520nm(0) for the green curve, 550nm(26) for the yellow curve and 450nm(20) for the blue curve. Maxima for the yellow and blue curves are more variable than those of the red and green curve.

Figures 7 through 10 show the chromatic response functions for JH, RS, RH and DM, respectively with all levels of purity superimposed on one graph. All curves are normalized to a chromatic response of 1.5 at 520nm on the green curve. If the relative heights of the curves remained constant with purity, then the curves for different purities would overlap. These figures show that the shapes and the relative heights of the curves vary with purity. For all subjects the shape of the red-green curve tends to be smooth and simple and to retain its shape with changes in purity (the exception is DM's green curve at a purity of 0.20 where the data point at 540nm would be an aberrant point if a smooth line were drawn through the data). For JH, RS and DM, the yellow-blue curves are not smooth and

their shapes tend to change with purity. RH is an exception to this with a smooth yellow-blue curve that tends to retain its smooth and simple shape for different purities.

At a purity of 1.0 in the long-wave region of the spectrum there is a wavelength where the red and yellow curves cross. This cross-over point represents equal red and yellow response. For wavelengths below this point there is greater yellow than red response and for wavelengths above this point there is greater red than yellow response (See Figures 3 through 6). For all observers, except DM, this cross-over point disappears at low purity, since yellow response is greater than or equal to the red response for all long wavelength lights.

Since the hue coefficient is a ratio of the magnitudes of the yellow-blue curve to the red-green curve plus the yellow-blue curve at a particular wavelength, changes in the relative heights of the curves with purity are reflected in changes in the hue coefficient with purity. Tables 2 through 5 are hue coefficients (predicted hue) for each of the test stimuli for JH, RS, RH and DM, respectively. These tables give the proportion of yellow or blue; the proportion of red or green can be found by subtracting from 1, since the two always add to one. Predicted hue is not consistent with purity for each wavelength. Table 6 gives the slopes of the linear regression equations for the predicted hue versus purity data contained in Tables 2 through 5. Although a line is not necessarily the best

fit to all the data, the sign of the slope shows the trend of increasing, decreasing or constant predicted hue with purity. A negative slope predicts a trend of increasing yellowness or blueness and of decreasing redness or greenness with decreasing purity, while a positive slope predicts a trend of decreasing yellowness or blueness and of increasing redness or greenness with decreasing purity. For observers JH, RS and RH predicted hue shows mostly negative slopes with the exception of JH at 480 and 580nm and RS at 560nm. These exceptions tend to be near the unique hues. These slopes predict a trend of increasing blueness or yellowness and of decreasing redness or greenness with decreasing purity. DM shows positive slopes, except for 540nm which is negative, that predict increasing redness or greenness and decreasing yellowness or blueness with decreasing purity.

Obtained Hue

The range of percent hue naming was computed for each of the stimuli (n=3). These ranges are displayed in Figures 11 through 14 as vertical error bars for subjects JH, RS, RH and DM, respectively. The mean range is 18.6 for JH, 22.3 for RS, 31.0 for RH and 27.4 for DM. The mean range for each purity ranges from 14.1 to 22.3 for JH, from 18.6 to 25.4 for RS, from 22.3 to 37.9 for RH and from 20.0 to 41.8 for DM. There is no systematic change in variability across wavelength between subjects, although different wavelengths tend to be more variable for different

subjects.

Tables 2 through 5 contain the results of hue naming (obtained hue) for each of the test stimuli for each observer. These tables show several ways that hue is not constant for different purities.

Generally the two hue names that an observer uses to describe a particular wavelength are the same for all purities, but exceptions to this rule occur for 480nm, 500nm and 580nm lights, which are near the unique hues. For all observers lights that appear blue-green at high purity are variable in appearance at the lowest levels of purity. The 480nm light appears blue-red sometimes at purities of 0.40 and 0.20 for JH, RS and DM and at a purity of 0.20 for RH. The 500nm light sometimes appears yellow-green at 0.60 for DM and at 0.20 for JH and DM. For observers RS and RH the 500nm light appears yellow-green for all levels of purity. For all observers the 580nm light always appeared yellow but across different levels of purity the appearance of this light varied from yellow-red to yellow-green.

Hue estimation (obtained hue) varies for different purities. Table 6 gives the slopes of the linear regression equations for obtained hue (%) versus purity for each wavelength. For all observers lights from 440nm to 480nm have a positive slope, while lights from 500nm to 640nm have a negative slope. DM is an exception with positive slopes for 580nm and 600nm lights. These slopes indicate

a general trend in change in the appearance of the spectrum with decreasing purity. For 440nm and 460nm light there is a decrease in blueness and an increase in redness. For 480nm light there is a decrease in blueness and an increase in greenness or redness with decreasing purity. For 500nm light there is an increase in yellowness or blueness and a decrease in greenness or redness. For 520nm lights and greater, lights that appear yellow-green and yellow-red, there is an increase in yellowness and a decrease in greenness or redness. The only exception is DM whose 580nm and 600nm lights decrease in yellowness and increase in redness or greenness with decreasing purity, but DM is highly variable in both the hue names assigned to these lights and in the range for percentage hue naming.

There is a tendency for wavelengths near unique blue and yellow to be more stable in the percentage of obtained hue for different purities. As can be seen in Table 6, 480nm and 580nm lights have the smallest slopes (the exception to this is RH at 480nm and DM at 580nm).

In general, lights of 440nm through 480nm decrease in blueness and increase in redness or greenness with decreasing purity, while lights of 500nm through 640nm increase in yellowness and decrease in redness or greenness with decreasing purity. Wavelengths near unique hues tend to be most stable for different purities.

Predictions of Hue

Figures 11 through 14 show the fit between predicted and obtained hue for JH, RS, RH and DM, respectively, at each purity. Predicted hue was computed using Equations 2 and 3 and each individual's chromatic response function at that particular level of purity. Table 7 gives the mean absolute difference and the correlation coefficient for predicted versus obtained hue for the different purities for each observer.

The fit between predicted and obtained hue is similar for purities 1.0 to 0.60. In Table 7 the mean differences are similar and there is a high correlation (p less than 0.001). At purities of 0.40 and 0.20 the predictions are not as close: the mean absolute difference is larger and the correlation is not significant (exceptions are relatively good fits for DM at 0.40 and 0.20 and for JH at 0.40). By these measures the model makes reasonably good predictions of hue comparable to those made at a purity of 1.0 except for the two lowest purities for some observers.

The model does not completely predict the Abney effect for any of the observers. This can be seen by comparing the slopes of the linear regression equations for predicted versus obtained hue in Table 6. For JH, RS and RH, the model does not predict the increasing redness and decreasing blueness of blue-red lights with decreasing purity, although the model does predict the increasing yellowness

and decreasing greenness or redness of yellow-green and yellow-red lights. For DM, the model predicts the increasing redness and decreasing blueness of blue-red lights with decreasing purity, although the model does not predict the increasing yellowness and decreasing greenness or redness of yellow-green and yellow-red lights with decreasing purity.

Achromatic Response

Figure 15 shows achromatic response functions as measured by heterochromatic flicker photometry for each observer. Log relative sensitivity is plotted versus wavelength. These results are compared to Judd's modified V_{λ} function, which is plotted on the same graph as diamonds joined by a solid line. All curves are normalized to 580nm. There is good agreement between the curves except in the short-wave region, where all observers show increased sensitivity relative to V_{λ} . This disagreement may be due to pre-receptoral filtering by macular pigment.

Obtained Saturation

Figures 16 through 19 are the results of saturation estimation for JH, RS, RH and DM, respectively. For a purity of 1.0 minimum saturation occurs at 560 to 580nm, and there is an inflection at 480nm. The exception to this is RS where 580nm is a secondary minimum and 440nm is the minimum. Also, the two longest-wavelength lights are more saturated than the two shortest-wavelength lights for all observers, except for RH where they are similar

in saturation. For all observers lights tend to decrease in saturation with decreasing purity, but the shape of the function does not remain the same. A second minimum forms at 480 to 500nm that becomes more prominent with decreasing purity. For RS and RH lights desaturate relatively little with decreasing purity compared to the results of JH and DM. For all observers 440 and 460nm lights desaturate least with decreasing purity.

The range was computed for the results of saturation estimation (%) for each test stimulus (n=3). These ranges are displayed in Figures 20 through 23 for subjects JH, RS, RH and DM, respectively. The mean range is 14.9 for JH, 14.2 for RS, 12.0 for RH and 21.8 for DM. The range did not change systematically with purity. The mean range for different purities ranged from 11.0 to 16.5 for JH, from 12.5 to 16.6 for RS, from 7.8 to 18.2 for RH and from 16.2 to 24.6 for DM.

Predictions of Saturation

Chromatic response measured at a particular level of purity was used to predict saturation at that level of purity. Saturation coefficients were computed for each level of purity according to the following equation which will be referred to as the linear valence model:

$$S_n = \frac{(|r-g|)_n + (|y-b|)_n}{(|r-g|)_n + (|y-b|)_n + a(w-bk)_n + (w-bk)_w} \quad (4)$$

where S is the saturation coefficient and $r-g$ and $y-b$ are the values of red-green and yellow-blue response, respectively. There are two $w-bk$ values: $(w-bk)_h$ is white-black response elicited by the monochromatic light as measured by HFP, and $(w-bk)_w$ is white-black response elicited by the white light, which is not measured experimentally. For a light of a purity of 1.0, for which no white light is added, $(w-bk)_w$ is zero. The constant 'a' represents the relative magnitude between the chromatic and achromatic systems.

Both the values of 'a' and $(w-bk)_w$ are free parameters and are chosen to achieve a best fit between the saturation coefficients and the saturation estimation data. The value of 'a' was chosen which gave a least-squares fit between the saturation coefficients and saturation estimation at a purity of 1.0. The value of 'a' was then fixed and $(w-bk)_w$ was then varied to achieve a least-squares fit between the saturation coefficients and saturation estimation for purity levels of 0.80 to 0.20.

In Table 8 are the mean absolute differences and correlations for saturation predicted by the linear valence model for each observer. The correlation coefficient shows if predicted and obtained saturation are related. Using an alpha level of 0.05, only RH at purities of 1.00, 0.80 and 0.60 and DM at purities of 1.00 and 0.20 show significant correlations. This indicates that in general predicted and obtained saturation are not related. The

mean absolute differences indicates an average deviation between predicted and obtained saturation. For JH, RS and DM there is not a systematic change in the mean difference with purity indicating a similar fit across purity. For RH there is an increasing lack of fit with decreasing purity ranging from a mean difference of 1.9 to 17.9. Also, RH shows the best fits of all observers at purities of 1.00 through 0.60.

Predicted and obtained saturation are compared in Figures 20 through 23 for JH, RS, RH and DM, respectively, for each purity. These figures show that in general the fit between predicted and obtained saturation is poor.

Figures 24 through 27 show the residuals for predicted verses obtained saturation for different purities for JH, RS, RH and DM, respectively. The residuals for the different purities are displaced vertically for clarity. Similar to Fuld (1991), a least-squares linear regression line is drawn through the residuals in order to demonstrate systematic trends of over-predicting and under-predicting saturation. At a purity of 1.0 for all observers the slope of the linear regression equation is negative (although RH has a relatively small negative slope) demonstrating that predicted saturation is overestimated for short-wavelength lights and underestimated for long-wavelength lights. In Figures 24 through 27 for different purities the slope tends to be negative as for a purity of 1.0 (except for small positive slopes for JH

at 0.40 and RS at 0.20 and positive slopes for DM at 0.40 and 0.60). The magnitude of the slope value decreases with decreasing purity for JH and RS, while for RH it increases, and for DM there is no change.

IV. DISCUSSION

Chromatic Response

The chromatic response functions for a purity of 1.0 are similar to those of previous studies. Werner and Wooten (1979b) determined an average opponent chromatic response based on seven color normal observers from several different studies. The wavelengths of maximum response for their average observer occur at 440nm and 610nm for red, at 530nm for green, at 580nm for yellow and 440nm for blue, which are similar to those found in the present study for spectral lights. Also, previous research, as well as the present study, found that the shape of the yellow-blue curve is more variable across observers than that of the red-green curve (Romeskie, 1978 and Werner and Wooten, 1979a).

For different purities the red-green curve tends to be smooth and to retain its shape, while the yellow-blue curve is not smooth and its shape tends to change for different purities. According to Ikeda and Ayama (1983) the smooth and simple shape of the red-green function can be well represented, while the yellow-blue curve because of its more complex shape, cannot be well represented by a linear combination of the color matching functions or the spectral sensitivity functions of the three cone types. Werner and Wooten (1979a) showed that the yellow-blue function could not be fit by a linear combination of the

three cone receptors. The results of the current study of the yellow-blue curve's lack of smoothness may be due to non-linearities in the yellow-blue mechanism. The departures from a smooth curve do not seem to be due to variability of the hue cancellation task, since there was no pattern of the yellow and blue curves being the most variable curves between subjects.

The present study found that chromatic response depends on purity. Since chromatic response is based on lights that appear unique in hue, this is consistent with previous studies that found that the wavelengths of unique hues change with purity (Ayama et al., 1987; Burns et al., 1984; Ikeda and Uehira, 1989; Kurtenbach et al., 1984). Do these differences in chromatic response predict differences in hue and saturation for different purities?

Obtained Hue

The variability in hue names applied to 480 and 500nm lights at low levels of purity and to 580nm lights at all levels of purity can be explained by the difficulty in detecting the minor hue component when it is a small proportion of total color. The minor hue component exists as a small proportion of total color at wavelengths that are near unique hue loci and at wavelengths that appear highly desaturated. The 580nm light is near unique yellow and tends to be one of the most desaturated hues at all levels of purity and is also variable at all levels of purity as either a yellow-green or a yellow-red. The 480

and 500nm lights are near unique blue and green loci and tend to be highly saturated at high purity, but at lower levels of purity they become among the most desaturated lights and the minor hue component becomes variable (red or green for 480nm and blue or yellow for 500nm). Werner and Wooten (1979a) also found that observers were variable in naming the minor hue component at wavelengths near unique hues.

The results of the present experiments depend on the particular white chosen as a desaturant. Perceptually unique white needs to be determined for individual observers. Since the present study uses the same xenon-white for all observers, it is not necessarily a perceptually unique white. If the white light used as a desaturant is not a perceptually unique white, then the chromatic component of the white light should affect hue. Both additivity and cancellation can occur by the admixture of the chromatic component of the white light and the chromatic component of the monochromatic light. For instance, if the white light appeared slightly bluish, then adding an increasing amount of this bluish-white to spectral lights should cause blue-red and blue-green lights to increase in blueness since there is additivity of blue, and it should cause yellow-green and yellow-red lights to decrease in yellowness, since there is opponent cancellation between blue and yellow.

Kurtenbach et al (1984) measured the Abney effect with

different desaturants: an individually determined unique white, two bluish-whites and a yellowish-white. They found that using any of the desaturants resulted in blue-red appearing lights becoming redder. Yellow-green lights became greener with a bluish-white desaturant and became more yellow with a yellowish-white desaturant. They found that the colors showing the smallest change in hue were yellow and blue-green. They found individual differences in the hue shifts for yellow-red lights. In the present study, the Abney effect is similar to Kurtenbach et al's (1984) results for a yellowish-white, except that they found individual differences for red-yellow lights and the present study found increasing yellowness with decreasing purity for all observers at red-yellow appearing wavelengths.

The present results in terms of the Abney effect can be explained by the additivity and cancellation of hue, assuming that the white light used as a desaturant was slightly yellowish. For blue-red lights increasing amounts of yellow in the yellowish-white cancel the blue causing the mixture to appear more red and less blue. For yellow-green and yellow-red lights increasing amounts of the yellow in the yellowish-white cause the lights to appear more yellow and less green or red. For blue-green lights the yellow in the yellowish-white cancels the blue in the monochromatic light so the light becomes more green and less blue with decreasing purity. Wavelengths near unique

yellow show a small Abney effect, since yellow is being added to yellow and there is no canceling of either the perceived red or green.

Does the desaturant appear yellowish? An additional experiment was performed to test this. Observers JH, RH and DM participated in this experiment. The stimuli were similar to those of the previous experiments, except that they included the xenon-white light alone plus admixtures of the xenon-white light and a 480nm light, yielding colorimetric purities (Equation 3) of 0 through 0.18 by steps of 0.02. The stimuli were presented four times in a random order, and the observer judged a stimulus as either yellow or blue. The stimuli consistently appeared yellow below and blue above a purity of 0.12, 0.16 and 0.04 for observers JH, RH and DM, respectively. Thus, the xenon-white alone appears yellowish, and the admixture of a 480nm 'blue' light cancelled this yellow.

The present results do not necessarily imply that if the desaturant were a perceptually unique white there would be no Abney effect. The relative contributions to the Abney effect of both the white and the hue of the desaturant should be considered in order to explain the Abney effect. The present study cannot make any strong conclusions about their relative contributions, since the appearance of the desaturant was not systematically varied and since the variability of hue naming may be too great for measuring an Abney effect due to a perceptually unique white.

Whatever the cause of the Abney effect as measured in the present study, this Abney effect is not being predicted by the hue coefficient.

Predictions of Hue

For a purity of 1.0, predicted versus obtained hue results compare favorably with Werner and Wooten (1979), which is encouraging, since the present study is based on less practice and fewer trials than Werner and Wooten's study. Their mean absolute differences between predicted and obtained hue range from 10.89 to 12.07 for their 3 observers, while in the present study they range from 11.5 to 13.7. Hue naming variance (r^2) attributable to opponent ratios ranges from 79% to 83% for Werner and Wooten's observers and from 76% to 83% for the present study.

The result of a good fit between predicted and obtained hue for most purities means that the model predicts hue to a good first approximation, even though the model does not predict the subtle Abney effect. The poor predictions at low purities for some observers may be due to difficulty in detecting hue both for cancellation and estimation when it is present in relatively small proportions.

DM's chromatic response functions and thus his predicted hue is different than the other observers, and his unique green is at a longer wavelength and more variable than other observers. The high variability indicates that DM has trouble distinguishing yellow-green from blue-green. This difficulty may have affected his chromatic response

functions when he had to cancel either the yellow or blue in greenish lights. Even though DM's chromatic response functions were different than other observers' the model predicted hue and saturation well for him. This suggests that individual differences in chromatic response were predictive of hue and saturation.

Obtained Saturation

The present results of saturation for varying purity can be compared to the results of Uchikawa et al. (1984) shown in Figure 1. Similar to their results, the present study found that lights tend to decrease in saturation with decreasing purity, and that a second minimum begins to form at about 480nm with decreasing purity. The present curves do not tend to flatten with decreasing purity as compared to those of Uchikawa et al. For RS and RH lights desaturate relatively little with decreasing purity compared to the results of JH and DM. For all observers, 440nm and 460nm lights desaturate relatively little with decreasing purity compared with the Uchikawa et al. data.

The differences between the saturation results of the present study and those of Uchikawa et al. may be due to different stimulus conditions. In the present study stimuli were equated according to V_{λ} , while Uchikawa et al. equated their stimuli on the basis of heterochromatic brightness matching. Since brightness and V_{λ} are not the same, especially for short-wave lights, this probably accounts for the discrepancy in obtained saturation between the

two studies in the short-wave region of the spectrum (Kaiser and Comerford, 1975; Uchikawa, Uchikawa and Kaiser, 1982; Uchikawa, Uchikawa and Kaiser, 1984).

Blue Light Control

What accounts for the minimum that forms on the saturation function at about 470nm with decreasing purity? Since Xenon-white is sometimes perceived as bluish, is the minimum caused by some unknown interaction between the monochromatic light and the bluish desaturating light? To test this hypothesis, an amount of blue appearing light was added to the test stimuli. In this additional experiment the stimuli and procedure were the same as that for Experiment 6, except that a 470nm light was added to the stimulus. In Equation 3 the Troland value of L_w remained the same as before but was now an admixture of 470nm light and xenon-white light at a purity of 0.50.

Figure 28 shows the results of saturation estimation for different purities with the blue appearing light added. These results can be compared to similar results without the added blue light (See Figure 16). The minimum that formed at 480nm with decreasing purity without the blue light does not occur with the blue light. Also, whereas saturation generally decreases with decreasing purity without the blue light, it does not do so consistently with the blue light added. For instance, 540 and 560nm lights are more saturated for a purity of 0.20 than for the other purities and for 480 and 500nm lights the order

from most saturated to least saturated is 0.60, 0.80, 0.20 to 0.40. The ends of the spectrum decrease in saturation with decreasing purity less with added blue light added than without it, while the middle of the spectrum decreases in saturation more with blue light added than without it. All these results are probably due to additivity and opponent cancellation between the chromatic component of the monochromatic light and the blue in the desaturant.

The result of the minimum at 480nm with decreasing purity is consistent with the xenon-white desaturant appearing yellowish. The opponent cancellation between the yellow in the desaturant and the blue in the 480nm light causes additional desaturation with decreasing purity that does not occur for yellow-green and yellow-red lights. For yellow-green and yellow-red lights the additional yellow added by the desaturant should cause these lights to desaturate relatively less with decreasing purity. Seemingly inconsistent with the above explanation are 440 and 460nm lights which appear blue but desaturate relatively little with decreasing purity compared to the 480nm light. As can be seen in Figures 3 through 6 blue chromatic response tends to be greater for 440 and 460nm lights than for the 480nm light with the exception of RS. Since the 480nm lights require relatively less yellow for opponent cancellation than 440 or 460nm lights, this may provide an explanation why the 480nm light desaturates relatively more with decreasing purity than the 440 or 460nm lights.

Predictions of Saturation

For a purity of 1.0, predicted saturation overestimates short-wavelength lights and underestimates long-wavelength lights, which is consistent with Fuld (1991). A similar lack of fit tends to exist for different purities.

The fit between predicted and obtained saturation is best for RH, and for him short-wave lights do not appear as desaturated relative to long-wave lights as is the case for the other observers. The model does not predict desaturated short-wave lights relative to long-wave lights for JH, RS and DM. Fuld (1991) suggested that the lack of fit between predicted and obtained saturation for a linear-valence model is due to rod intrusion and a non-linearity of one of the opponent mechanisms. He found that he could improve the fit between predicted and obtained saturation by using a nonlinear, rod model:

$$S_r = \frac{a(|r-g|)^n + b(|y-b|)^n}{a(|r-g|)^n + b(|y-b|)^n + c(w-bk) + d(V_r')} + k \quad (5)$$

where a , b , c , d , n and k are free parameters which were allowed to vary in order to achieve a best fit, and V_r' was the scotopic spectral sensitivity function. The present study also improved predictions of saturation with Equation 5. Table 8 shows that, compared to the linear valence model, the nonlinear, rod model improves the fit in terms of the mean absolute difference and the correlation

coefficient, except for RH at purities of 1.0 through 0.6 and DM at a purity of 0.2.

In the present study an additional experiment was performed in order to test the rod intrusion hypothesis. Spatial and temporal stimulus parameters were varied in order to manipulate the extent of rod contribution. Stimulus parameters that favor rod contribution, a field size larger than the fovea and a relatively long presentation time, should weaken the model's predictions, while stimulus parameters that do not favor rod contribution, a field size smaller than the fovea and a relatively short presentation time, should improve the model's predictions.

Only JH participated in this experiment. A similar procedure as in Experiments 2 through 6 was followed except that only lights of a purity of 1.0 were tested and four different test stimulus conditions were tested. They were: a 2.6-deg field presented 1 second every 5 seconds, a 2.6-deg field presented 2 seconds every 5 seconds, a 0.6-deg field presented 1 second every 5 seconds and four, a 0.6-deg field presented 9 milliseconds every 4 seconds.

Table 9 presents the four different test conditions. The conditions will be referred to by the letters, A through D, contained in Table 9.

Figure 29 shows chromatic response functions for each of the conditions superimposed on one graph. The yellow curves, as found before, are not smooth. The wavelength

of maximum response for the yellow curve is at at 560nm for all conditions except for condition D, where it is at 600nm. The location of unique yellow, as defined by where the red-green curve is at zero in the long-wave region of the spectrum, is closer to 560nm for condition D, while it is closer to 580nm for the other conditions. The functions for the different conditions are not identical, especially toward the spectral extremes for the red-green curve. Because of these differences, each function makes different predictions of hue. As seen in Table 10, there are differences in predicted hue from one condition to another. The predictions of hue, in Table 10, are similar for conditions A and B, the large field, while those for conditions C and D, the small field, tend to be different from each other and from A and B.

The range of hue naming (%) was calculated for each of the test stimuli (n=3). These ranges are displayed as vertical bars in Figure 30. The mean ranges for the different conditions are listed in Table 9. The smaller field is more variable than the larger one, and within the same size field the longer duration stimulus tends to be more variable than the shorter duration.

Figure 30 shows the fit between predicted and obtained hue. These fits are similar to that shown in Figure 11 for a purity of 1.0. Table 9 gives the mean absolute difference and the correlation between predicted and obtained hue for each of the conditions. For all conditions

there is a relatively good fit between predicted and obtained hue. In conditions A, B and C the fits are similar, while the fit for condition D is slightly worse than the other three.

The variances (r^2) in hue naming accounted for by the model are 73%, 76% and 72% for conditions A, B and C, respectively, while it is 53% for condition D. The correlations show that predicted and obtained hue are related (p is less than or close to 0.01). The correlations tend to be lower and the mean absolute differences tend to be higher for these conditions than for those obtained for JH at a purity of 1.00 in the Experiment 4 (see Table 7), but they are still a relatively good fit.

Figure 31 shows achromatic response for conditions A, B and C. It was not possible to do HFP for condition D due to the short presentation time. HFP results for condition C were used for condition D predictions. The three conditions show similar results, and they tend to deviate from V_λ at the short wavelengths. This is consistent with JH's achromatic response in Experiment 5 (see Figure 15). Favoring rods, as for condition A and especially B, should cause the achromatic response function to shift to the shorter wavelengths, but this was not the case.

The range of saturation estimation (%) was calculated for each of the test stimuli ($n=3$). These ranges are

displayed in Figure 32 as vertical bars. The mean range for each condition is contained in Table 9. Condition A, the large field size and short duration, is the most variable condition.

Figure 32 shows the fit between predicted and obtained saturation for the different conditions. Table 11 lists the values for predicted and obtained saturation. The fit between predicted and obtained saturation (see Table 9), as measured by the mean absolute difference is better for the C and D conditions than for the A and B conditions and as measured by the correlation coefficient is best for condition D. The combination of smallest field size and the shortest duration gives the best fit between predicted and obtained saturation.

Figure 33 shows obtained saturation verses wavelength for each condition. Obtained saturation differs across conditions in a number of ways. Minimum saturation is at 560nm for all conditions, but for conditions A, B and C there is a secondary minimum in the short-wave region of the spectrum. Short-wave lights appear more saturated in conditions C and D than in conditions A and B. The 560nm light is much less saturated in condition D than in the other conditions. Short-wave lights tend to be less saturated than the long-wave lights for all conditions except D. The slope of the linear regression line for the residuals verses wavelength displayed in Figure 34 and contained in Table 9 indicates that for all conditions

there is a negative slope indicating that predicted saturation overestimates short-wave lights and underestimates long-wave lights. This negative slope is smaller in magnitude for condition D. A comparison of Figure 34 with the same results for JH in the previous experiment in Figure 24 shows the same pattern of mismatch for the residuals about the regression line.

These results support the hypothesis that the rods contribute to saturation, since the predictions are improved by conditions that minimize rod contribution. Achromatic response and hue remained relatively unaffected by the different stimulus conditions. Since the effect occurs for saturation, this indicates that if the effect is due to rod contribution, then the rods are affecting only saturation and not hue and achromatic response (as defined by HFP) under these conditions.

In the present study, stimulus size mostly affected short-wave lights. This means that if the differences in saturation due to stimulus size are due to rod contribution, then the desaturating signal from the rods influences short-wave lights. Different from the present results and opposite of what would be expected if the rods contributed to a desaturation of the spectrum, previous researchers found that for foveally viewed stimuli, increasing the test-field size causes an increase in saturation for the entire spectrum (Gordon and Abramov, 1977; Burnham, 1951 and 1952; Stevens, 1934). Since none

of the above studies investigated a full range of test-field sizes and wavelengths, differences in the results may be due to the particular sizes and wavelengths used in the studies. Saturation might not change in a monotonic sequence with test field size, and saturation may not change equally for different wavelengths.

For peripherally viewed stimuli, Gordon and Abramov (1977) and Abramov et al (1991) found that a test field becomes desaturated with increasing eccentricity. As they increased the size of the peripherally viewed stimulus saturation increased to become similar to foveal saturation. These results are not consistent with the rod contribution hypothesis since increasing the size of a foveally viewed stimulus and increasing the eccentricity of a stimulus both lead to an increasing contribution by the rods, but each has a different effect on saturation. However, increasing the size of a foveally viewed stimulus affects spatially the population of cones as well as rods contributing to the sensation.

The results of this study and those of previous studies suggest further investigation of the relationship between saturation and field size and eccentricity. Future research should investigate a fuller range of stimulus parameters and their effect on saturation and investigate the mechanisms that account for the effect.

The model's predictions may also be improved by a different method of measuring achromatic response. Unlike

chromatic response which is based on a perceptual criterion of yellow or blue and red or green, V_{λ} as measured by HFP is not based on observations of white or black. There may be another characterization of achromatic response based on judgments of white and black that would improve the predictions of the model.

There may be a model that predicts hue and saturation better than the Jameson and Hurvich model. Other opponent-color vision models predict hue and saturation for the spectrum (Guth et al. 1980 and Hunt, 1982) and predict the Abney effect (Guth, 1991). Since these models start with the spectral sensitivity functions of the three cone photopigments, they cannot be directly applied to predicting hue and saturation based on individually measured chromatic and achromatic response functions.

V. CONCLUSION

The present study is unique in that it tests predictions by the Jameson and Hurvich model of both hue and saturation for both spectral and non-spectral lights. The model predicts hue to a good first approximation, except at the two lowest purities for some observers, but does not predict the subtle Abney effect. The model makes relatively poor predictions of saturation, tending to over-estimate the saturation of short-wave lights and to under-estimate that of long-wave lights. Both the results of the Abney effect and the second minimum forming on the saturation function at 480nm with decreasing purity are consistent with the opponent-cancellation and additivity between the yellowish-white desaturant and the spectral lights. An additional experiment demonstrates that predictions of saturation are improved by stimulus parameters that minimize rod contribution, suggesting a possible rod contribution to saturation.

VI. FIGURES

Figure 1. Saturation versus wavelength for purities of 1.0(+), 0.9(X), 0.7(*), 0.5(square), 0.3(diamond) and 0.1(triangle). These results were plotted by the present author with results from Uchikawa et al. (1984).

Figure 1.

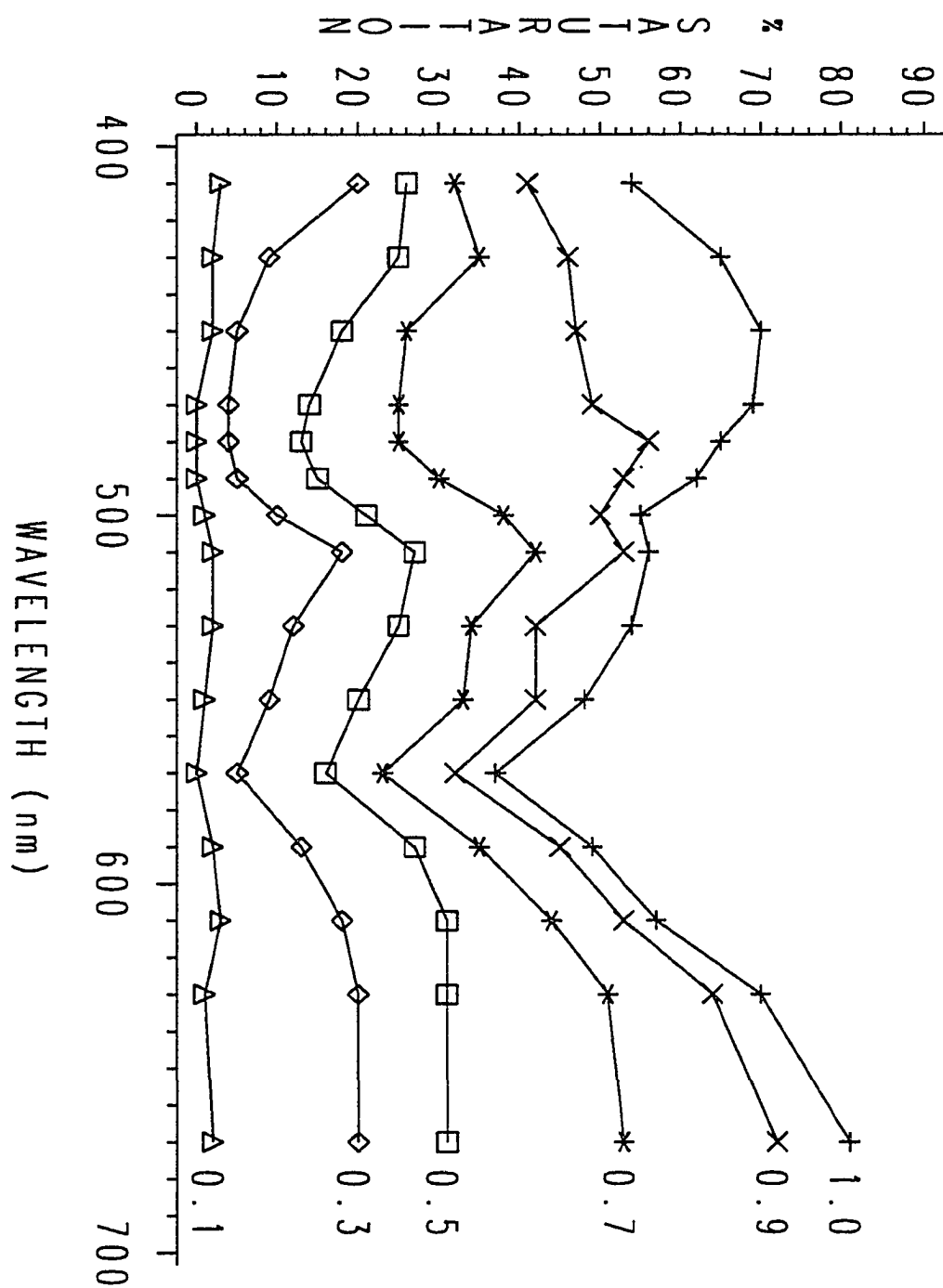


Figure 2. Schematic diagram of the apparatus. See text for details.

Figure 2.

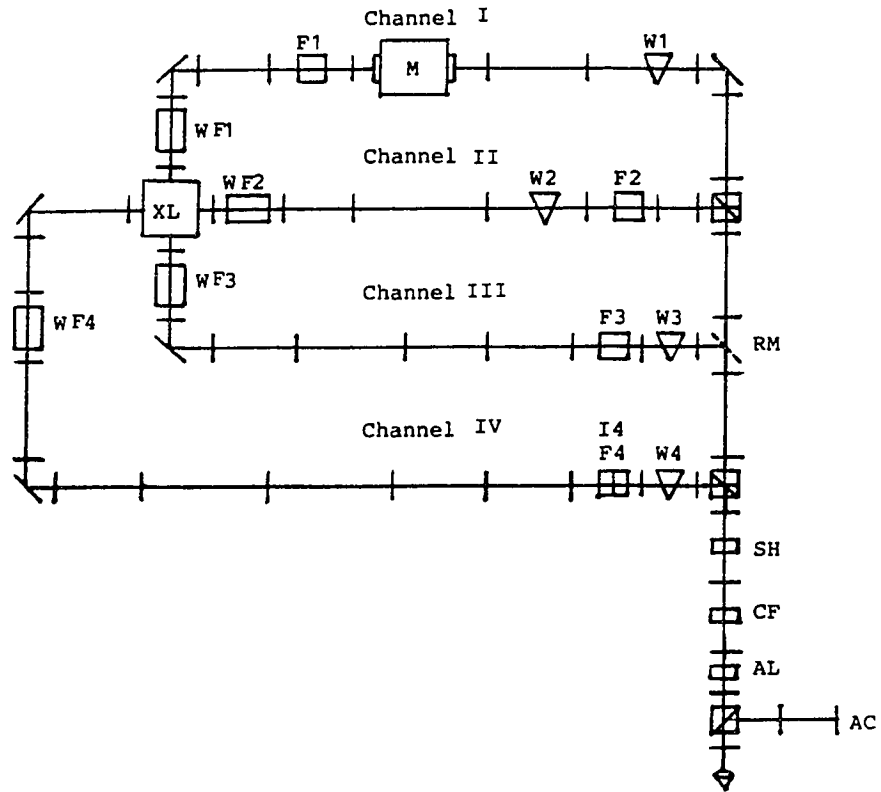


Figure 3. Relative chromatic response functions measured by hue cancellation (experiment 2) at purities of 1.0 (panel A), 0.80 (panel B), 0.60 (panel C), 0.40 (panel D) and 0.20 (panel E). Each symbol, yellow-blue (X) and red-green (star) represents the mean of two measurements. The relative heights of the curves were adjusted according to procedures described in the text using the data of experiments 3 and 4. All curves are normalized to a chromatic response of 1.5 at 520nm on the green curve. Observer is JH.

Figure 3.

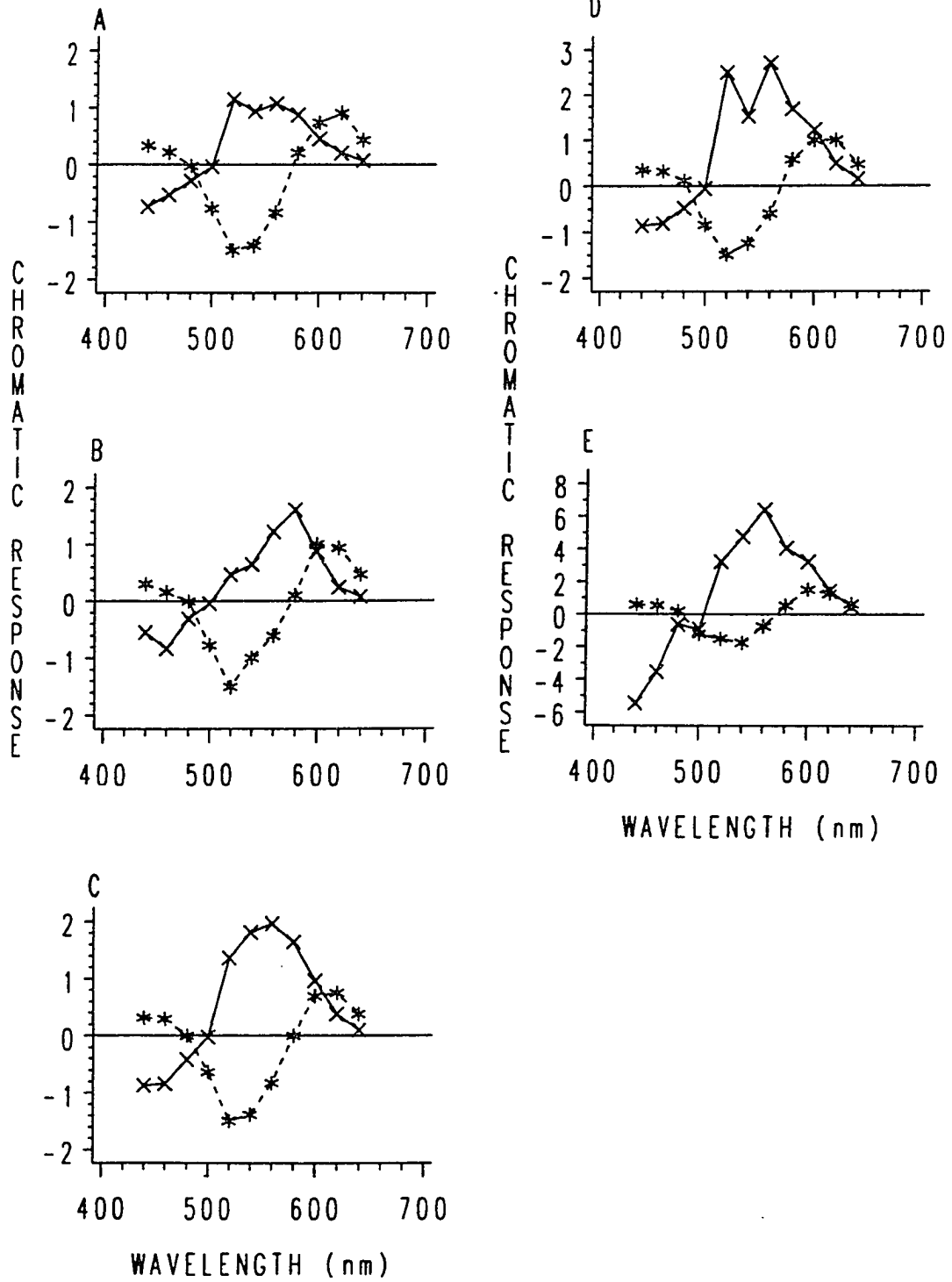


Figure 4. Same as Figure 3, for observer RS.

Figure 4.

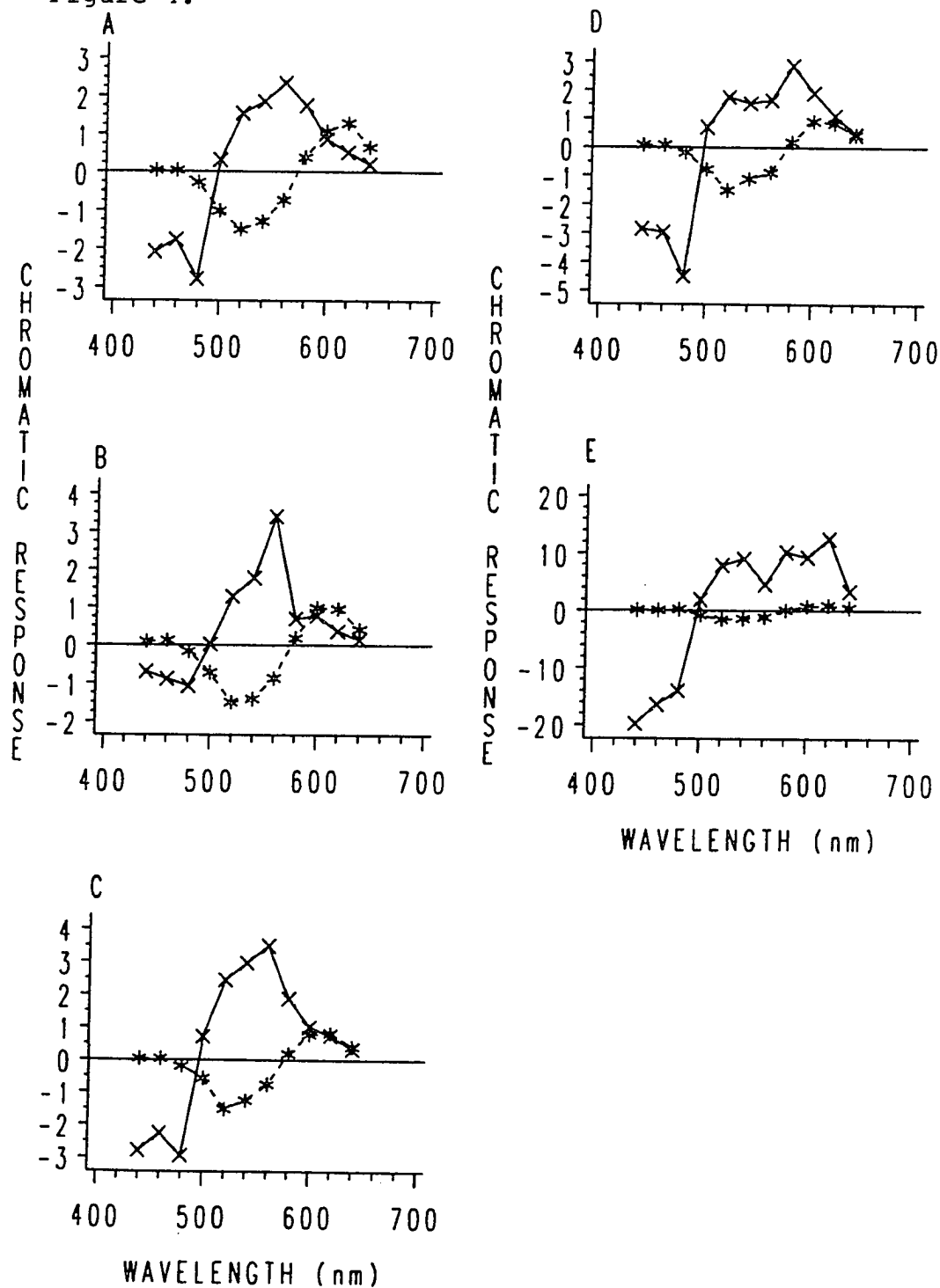


Figure 5. Same as Figure 3, for observer RH.

Figure 5.

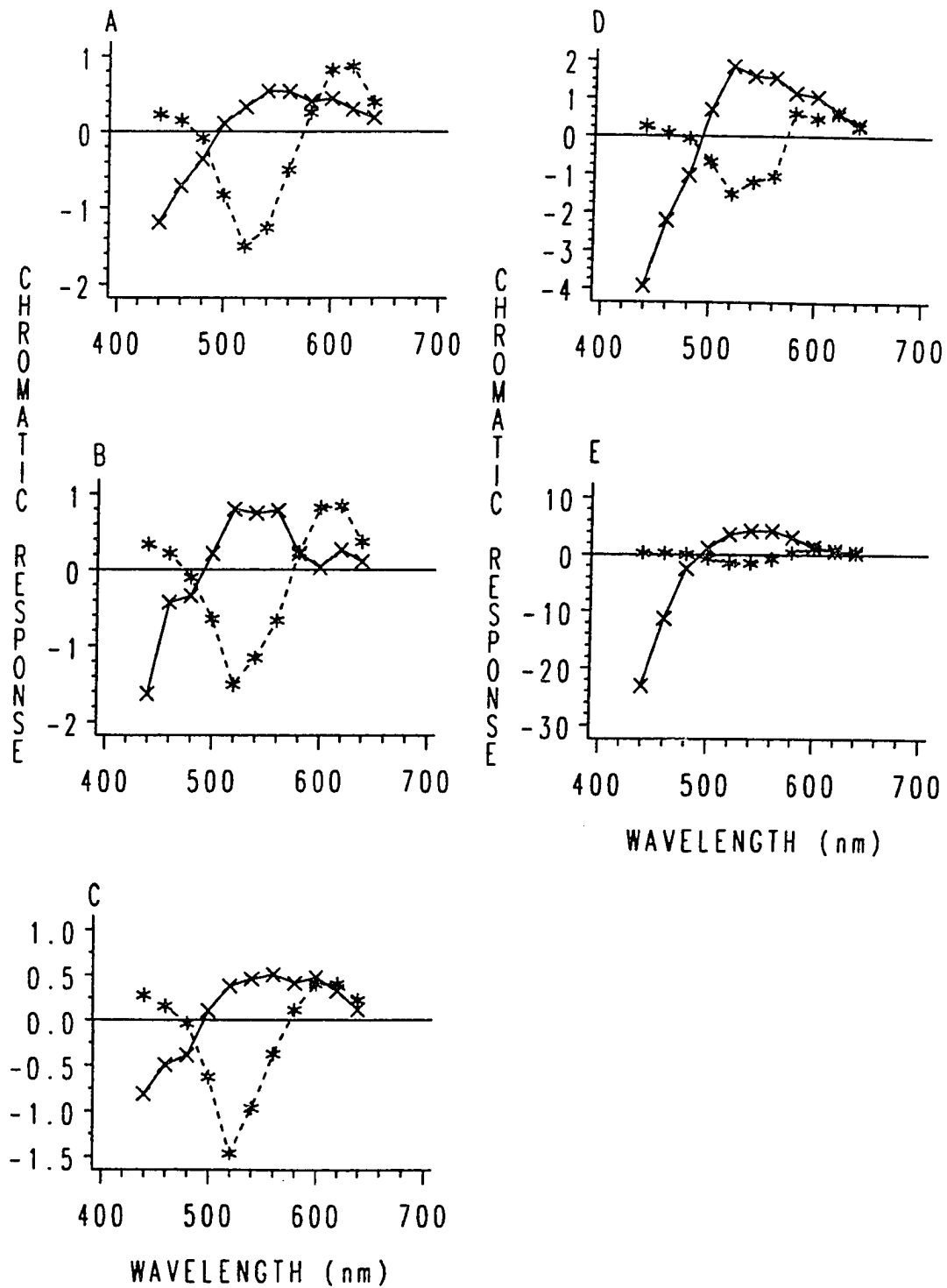


Figure 6. Same as Figure 3, for observer DM.

Figure 6.

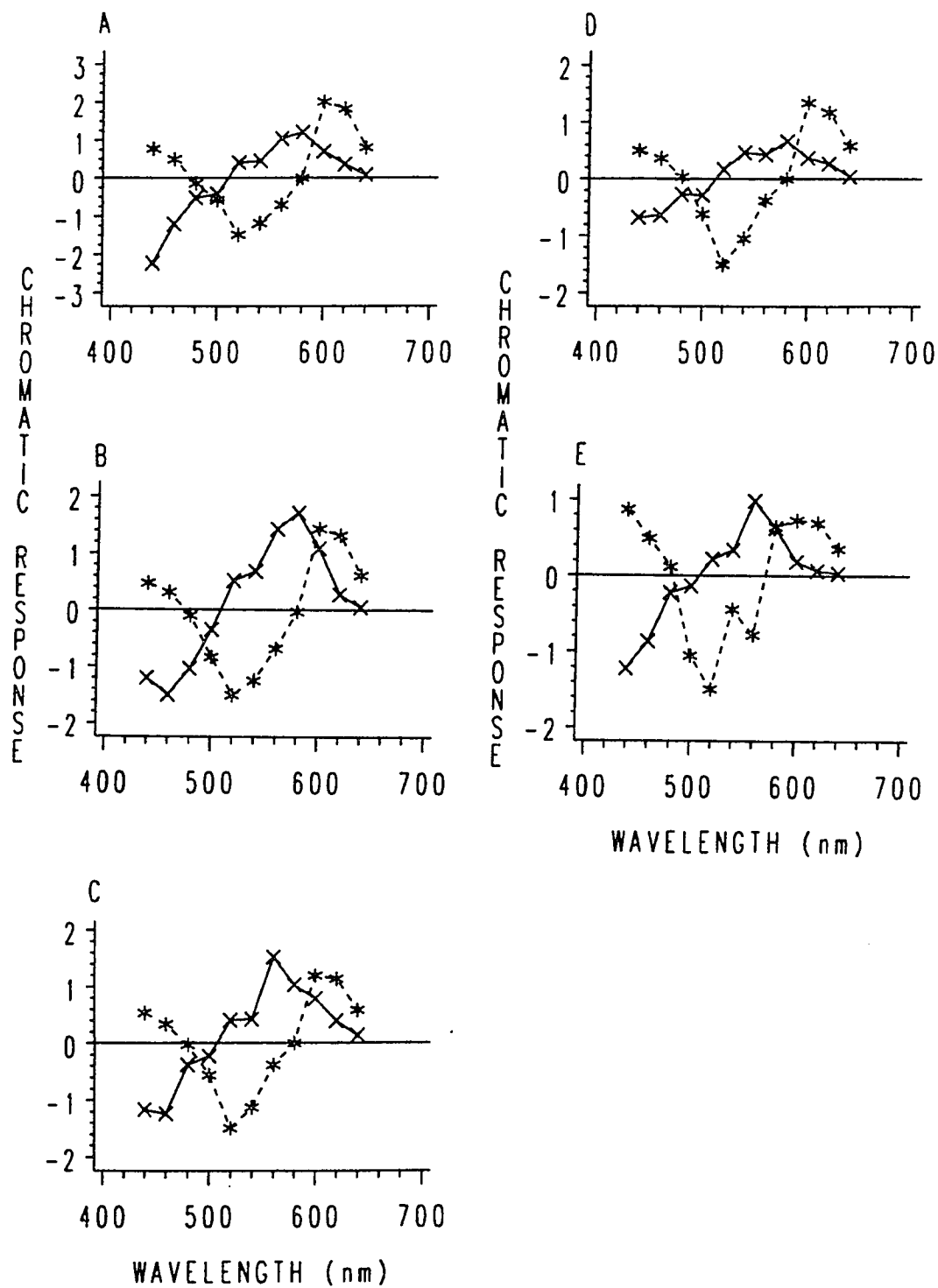


Figure 7. Same as Figure 3 except all purities are superimposed on one graph. Yellow-blue(solid line) and red-green(interrupted line) chromatic response functions for purities of 1.0(+), 0.80(X), 0.60(*), 0.40(square) and 0.20(diamond). Observer is JH.

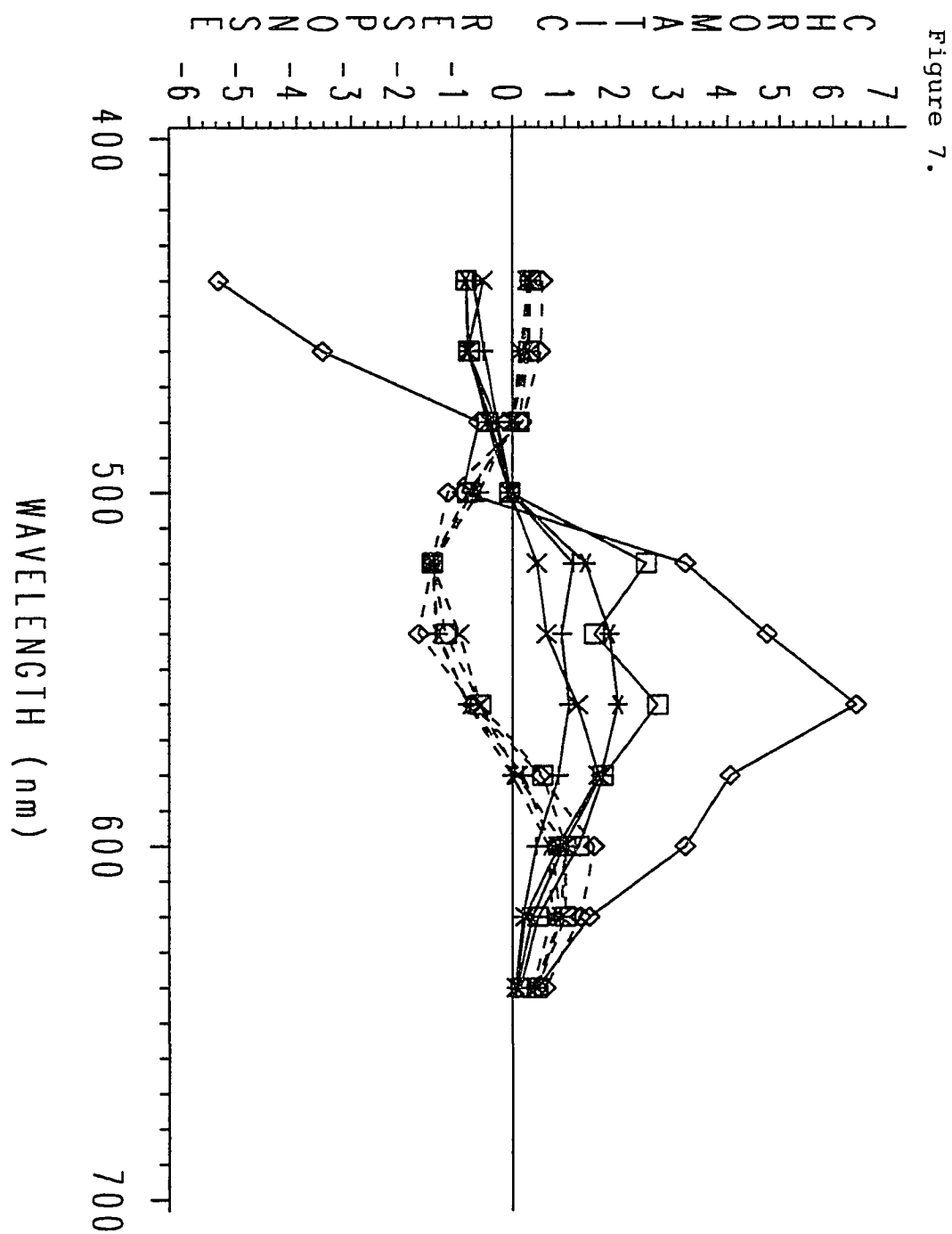


Figure 8. Same as Figure 7, for observer RS.

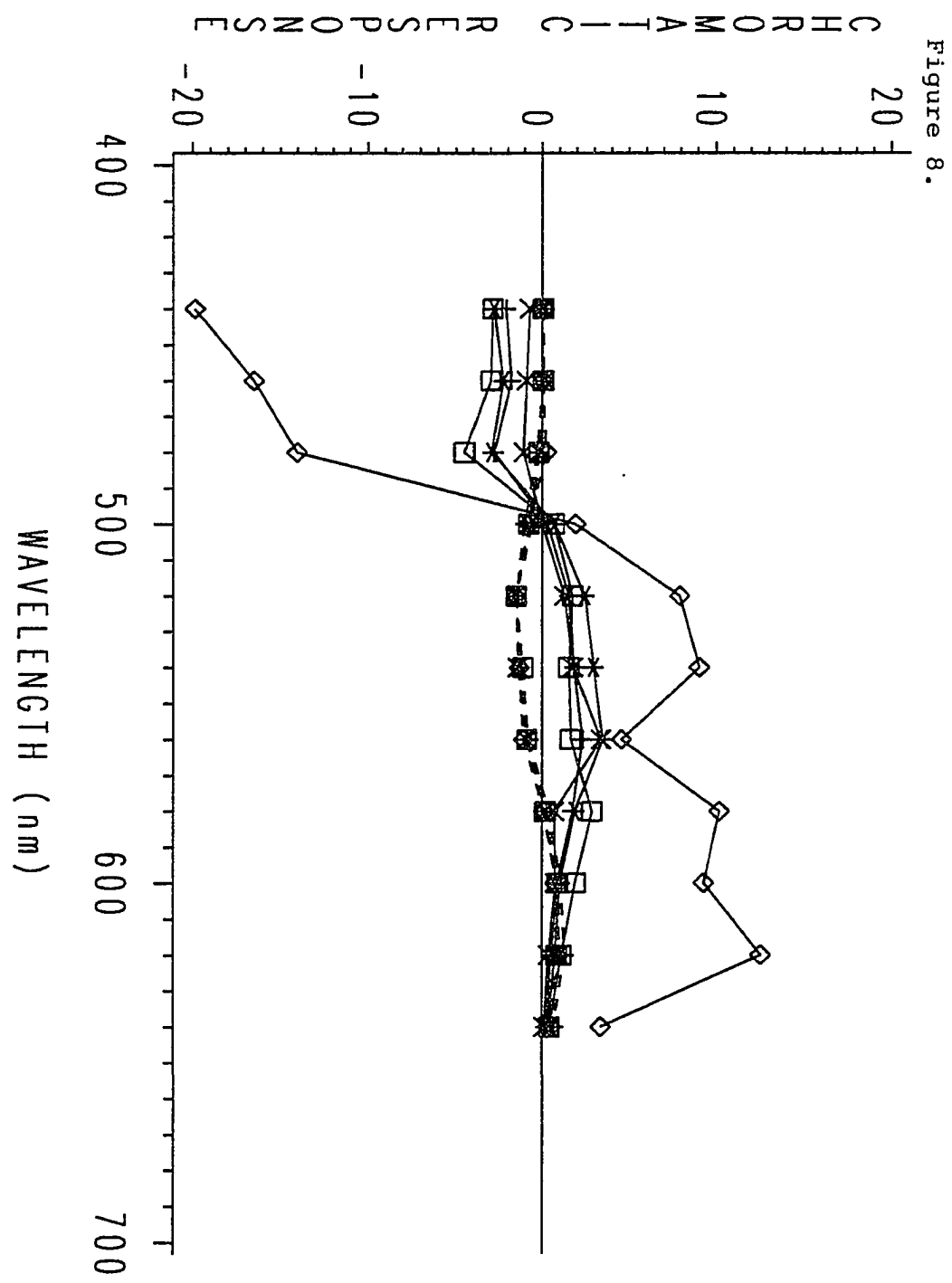


Figure 9. Same as Figure 7, for observer RH.

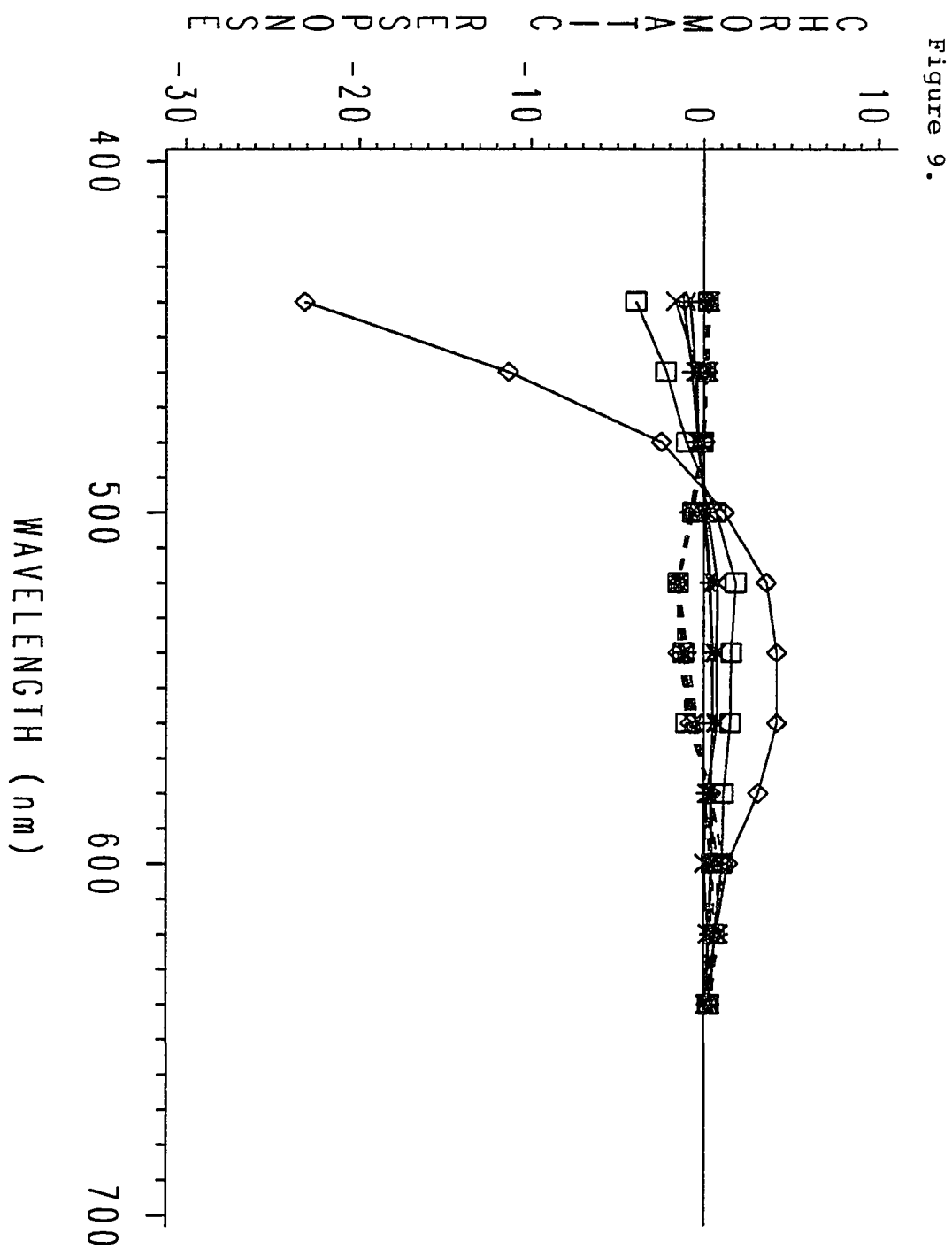


Figure 10. Same as Figure 7, for observer DM.

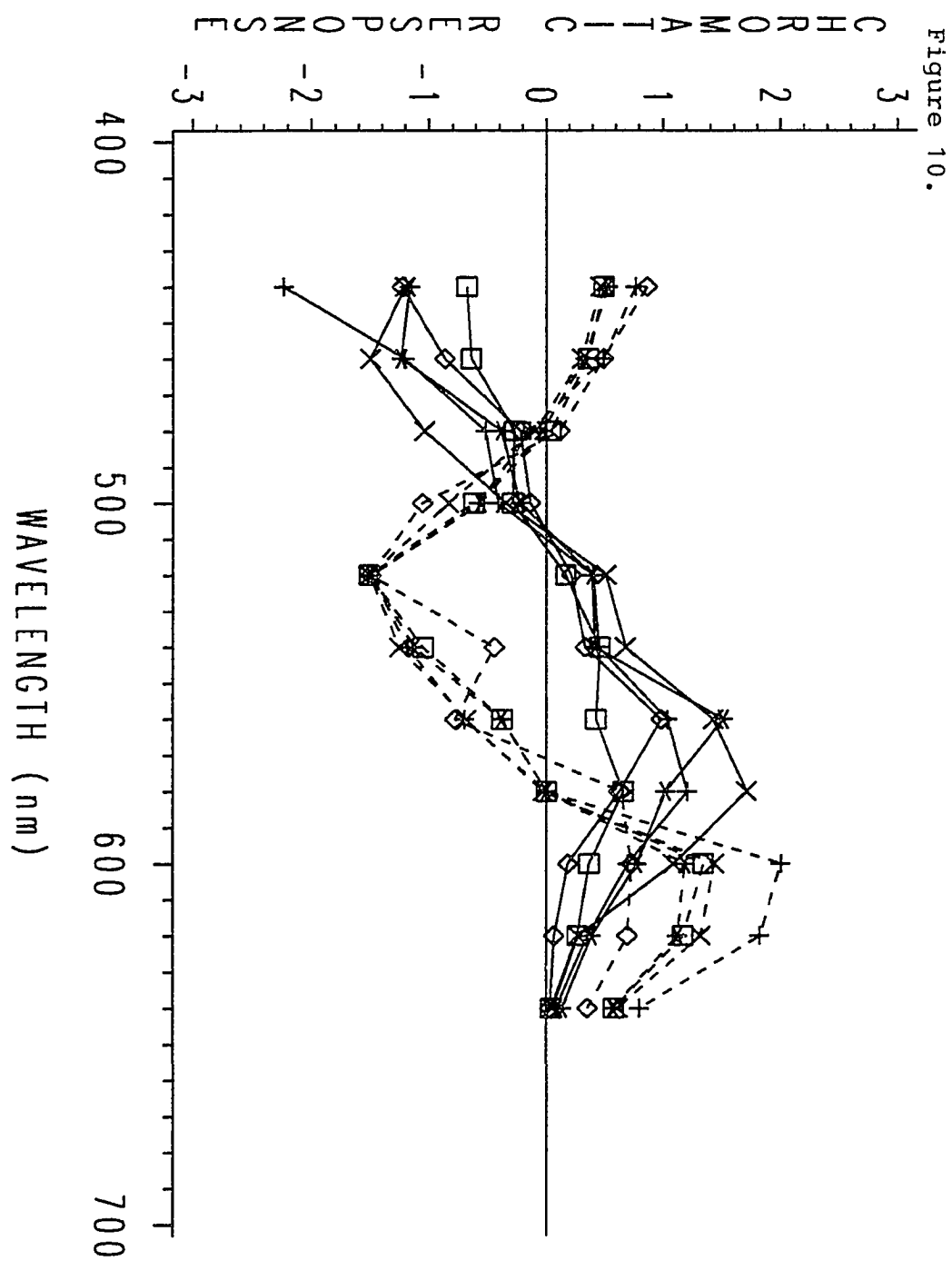


Figure 11. Percentage of hue versus wavelength for the hue naming data of experiment 4 (solid line connects the mean and vertical lines are the ranges for each wavelength) and for predicted hue (square) at purities of 1.0 (panel A), 0.80 (panel B), 0.60 (panel C), 0.40 (panel D) and 0.20 (panel E). Predicted hue was computed from equations 2 and 3 and the chromatic response function for the respective purity. The percentage of red or green is plotted on the left vertical axis and the percentage of yellow or blue is plotted on the right vertical axis. Observer is JH.

Figure 11.

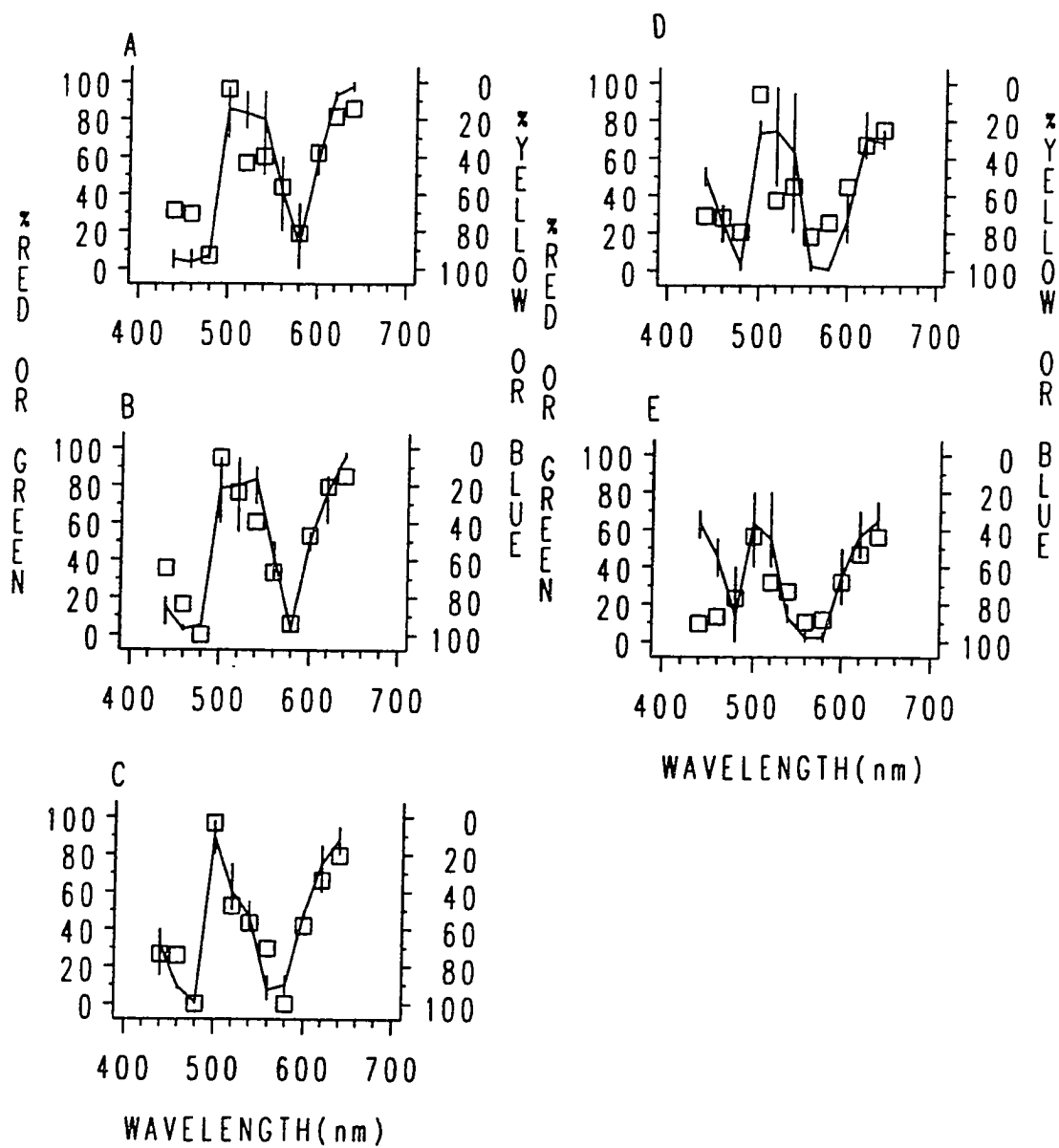


Figure 12. Same as Figure 11, for observer RS.

Figure 12.

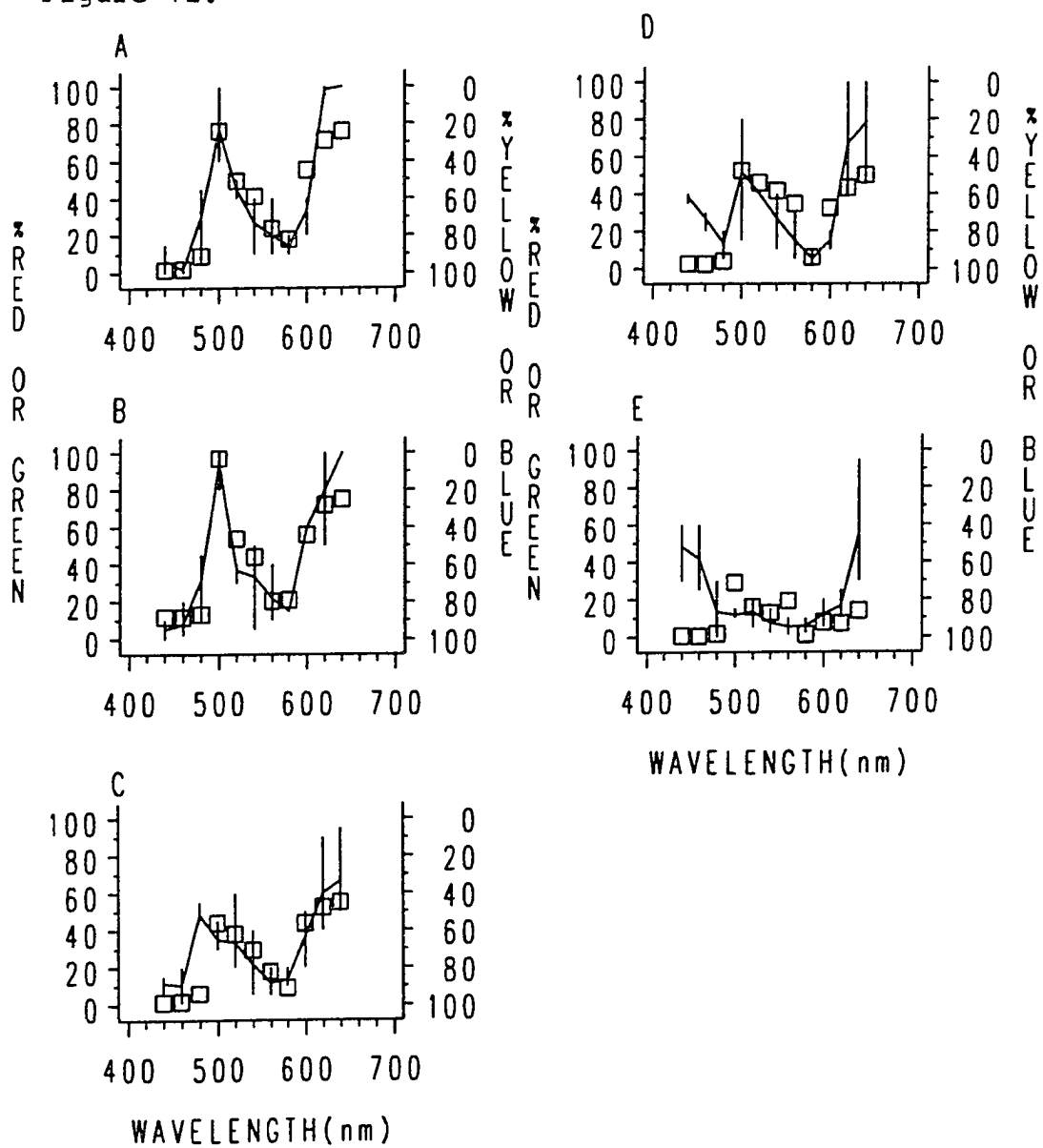


Figure 13. Same as Figure 11, for observer RH.

Figure 13.

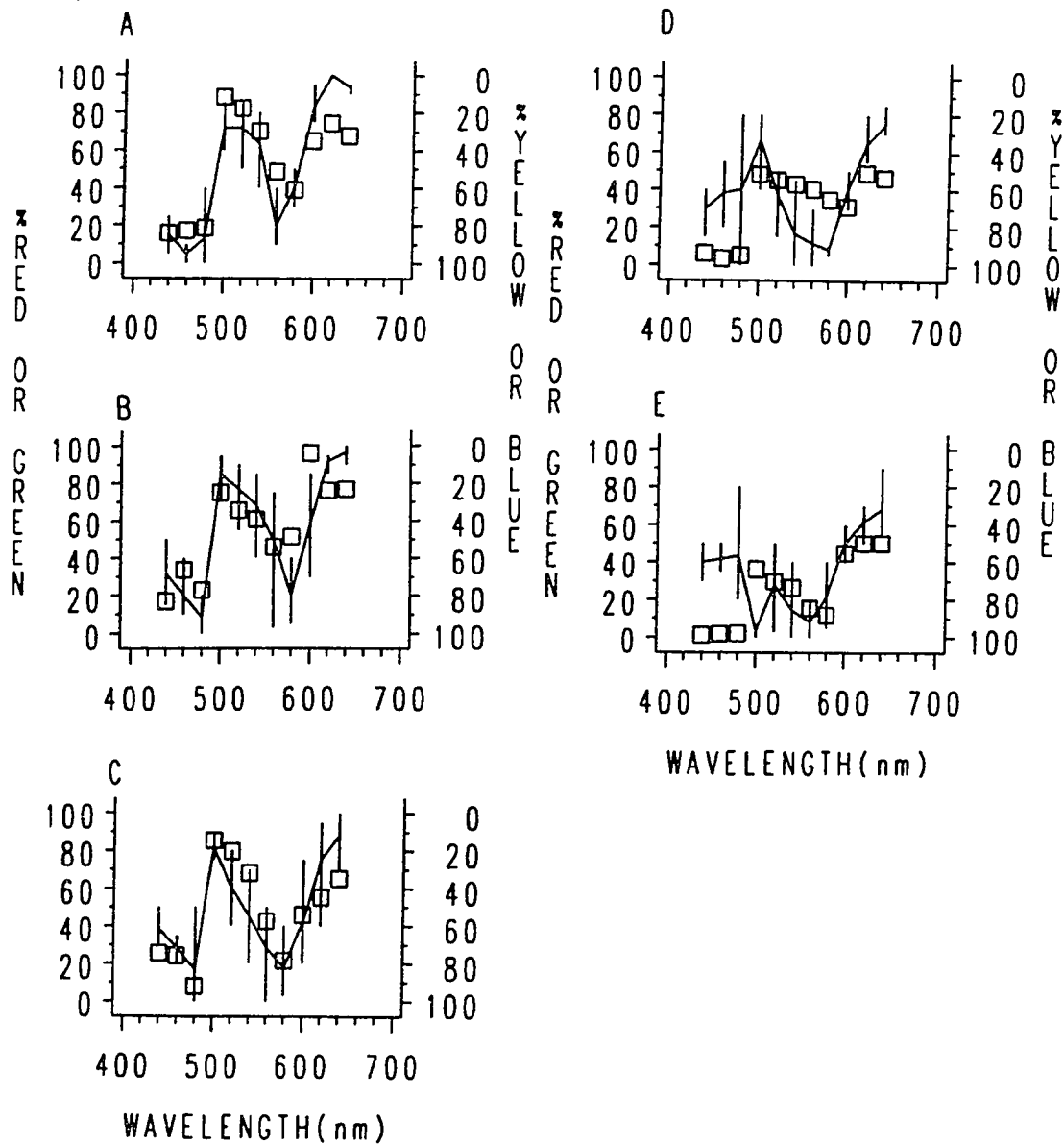


Figure 14. Same as Figure 11, for observer DM.

Figure 14.

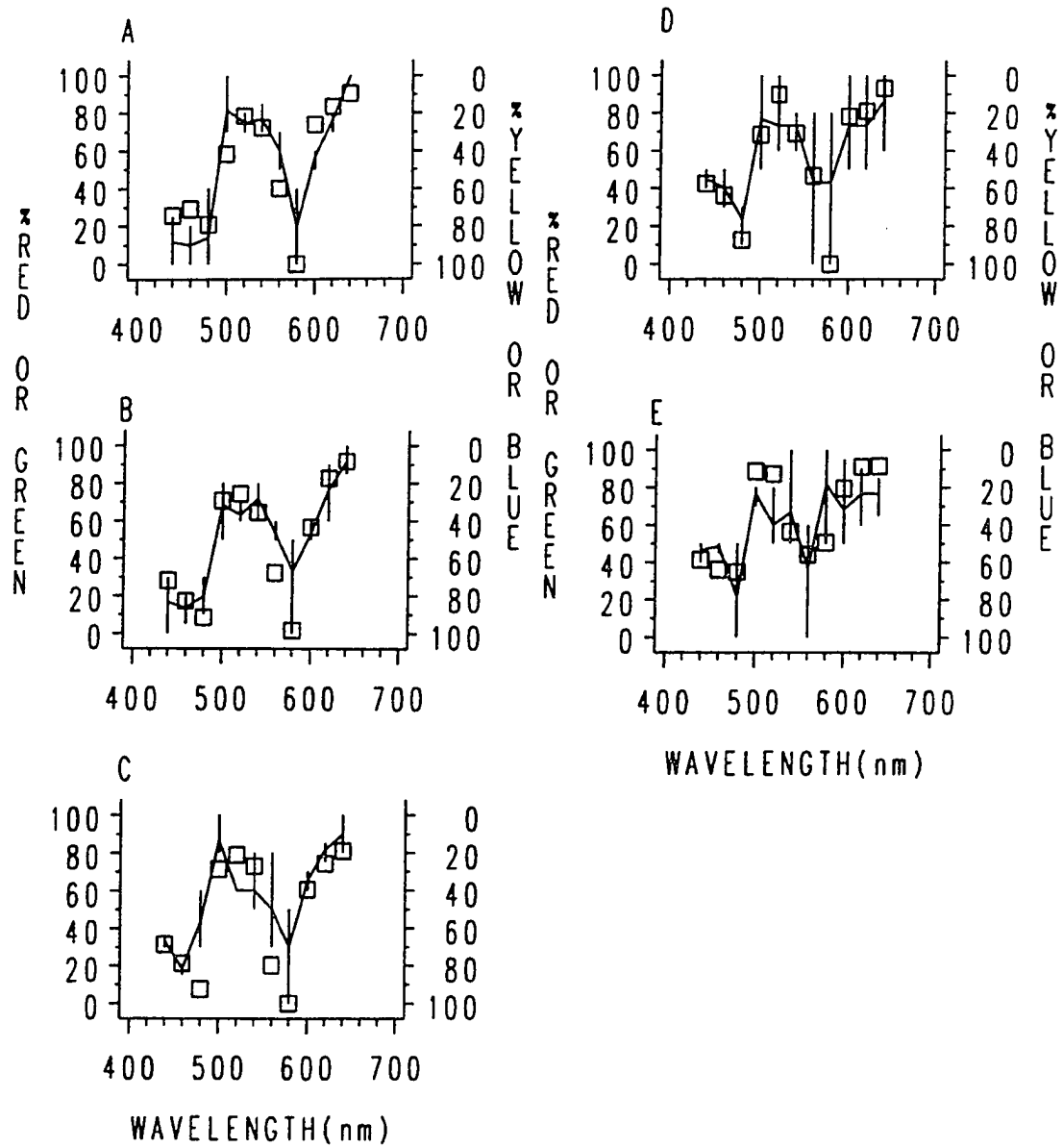


Figure 15. Achromatic response measured in experiment 5 for subjects JH(*), RS(+), RH(X) and DM(square). Log relative sensitivity is plotted versus wavelength. All curves are normalized to 580nm. Judd's modified V_λ function(diamond) is plotted for comparison.

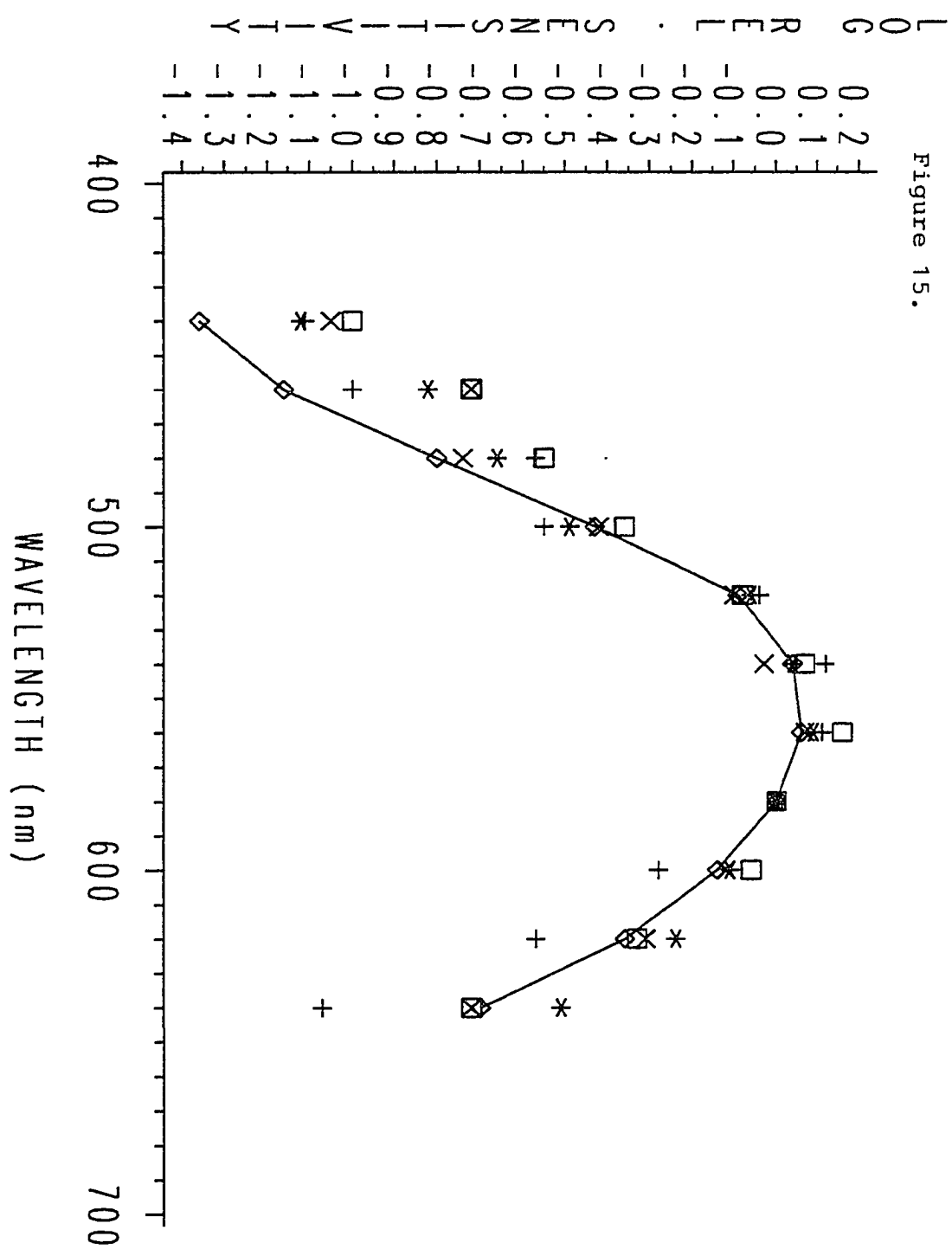


Figure 16. Percentage of saturation versus wavelength for different purities: 1.0 (plus), 0.80 (X), 0.60 (*), 0.40 (square) and 0.20 (diamond). These are the results of experiment 6, saturation estimation. Each point is the mean of three responses. Observer is JH.

Figure 16.

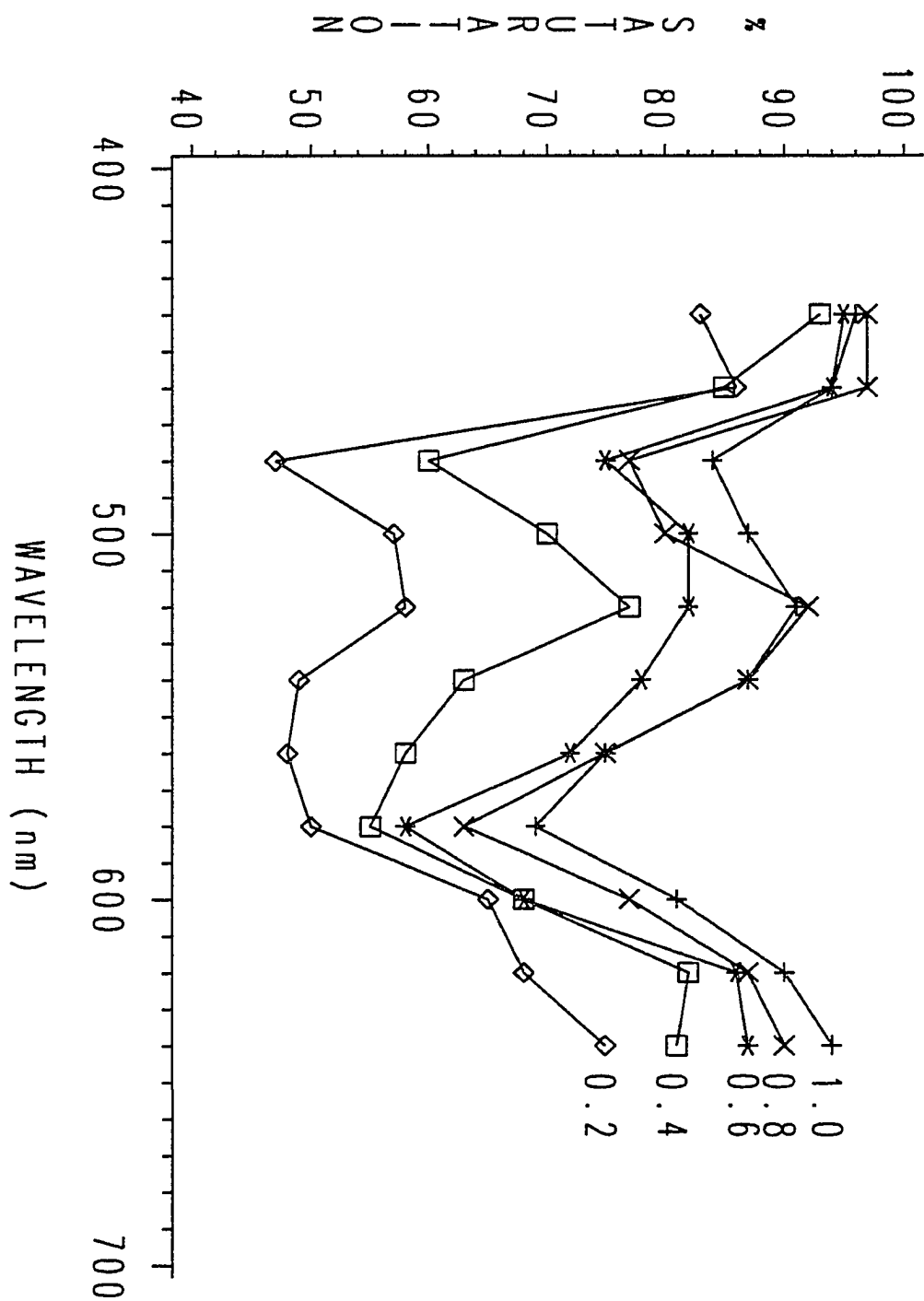


Figure 17. Same as Figure 16, for observer RS.

Figure 17.

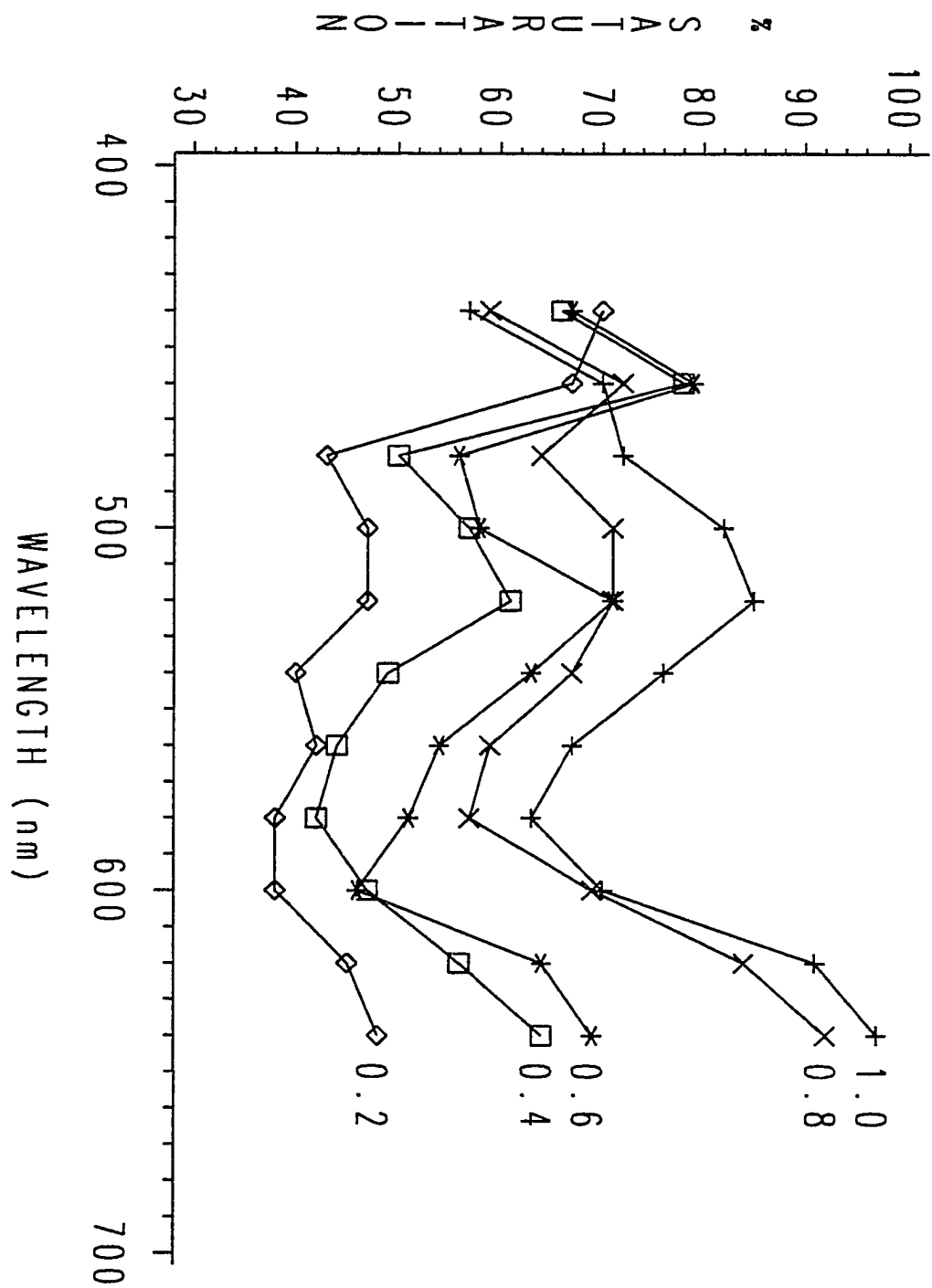


Figure 18. Same as Figure 16, for observer RH.

Figure 18.

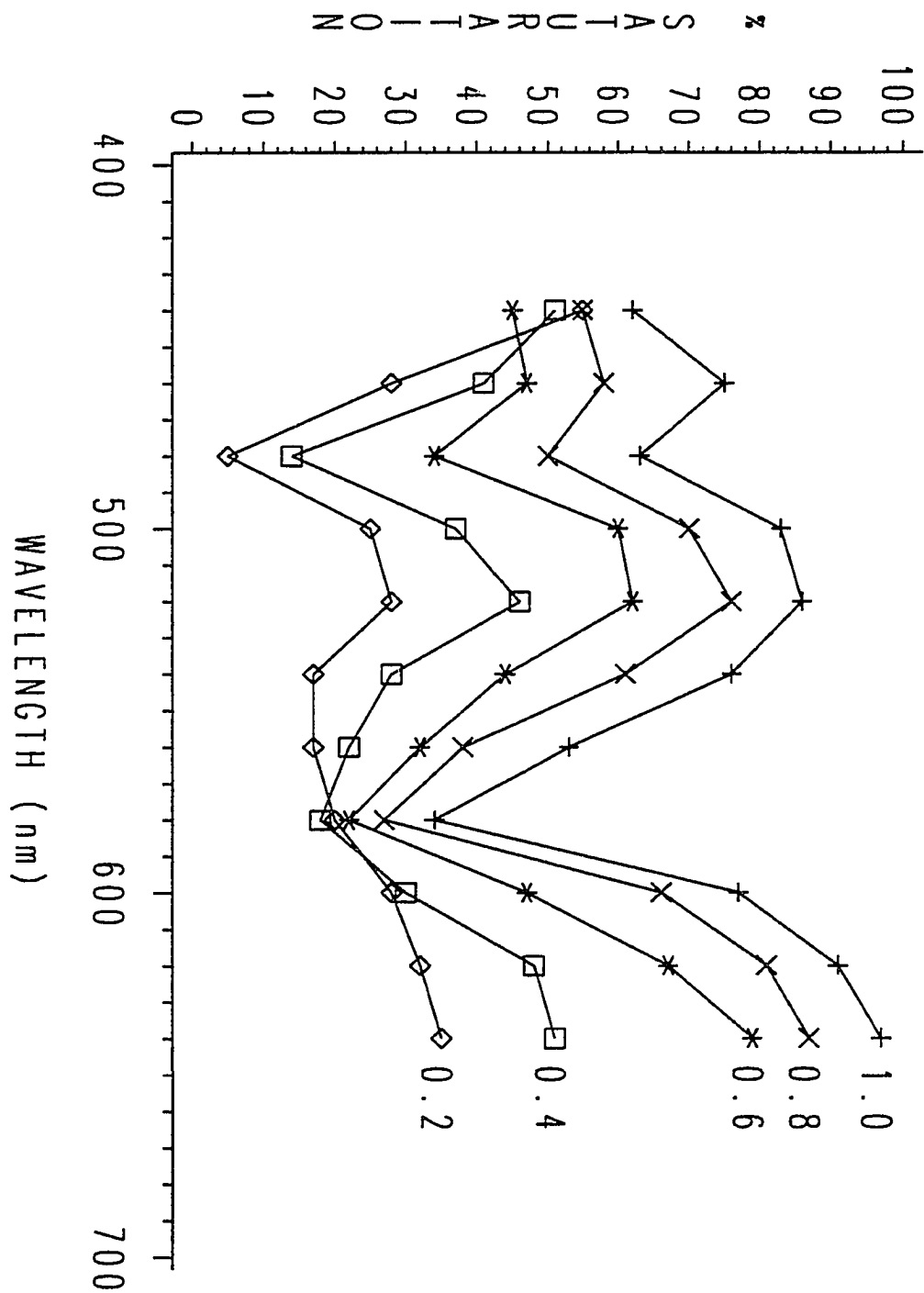


Figure 19. Same as Figure 16, for observer DM.

Figure 19.

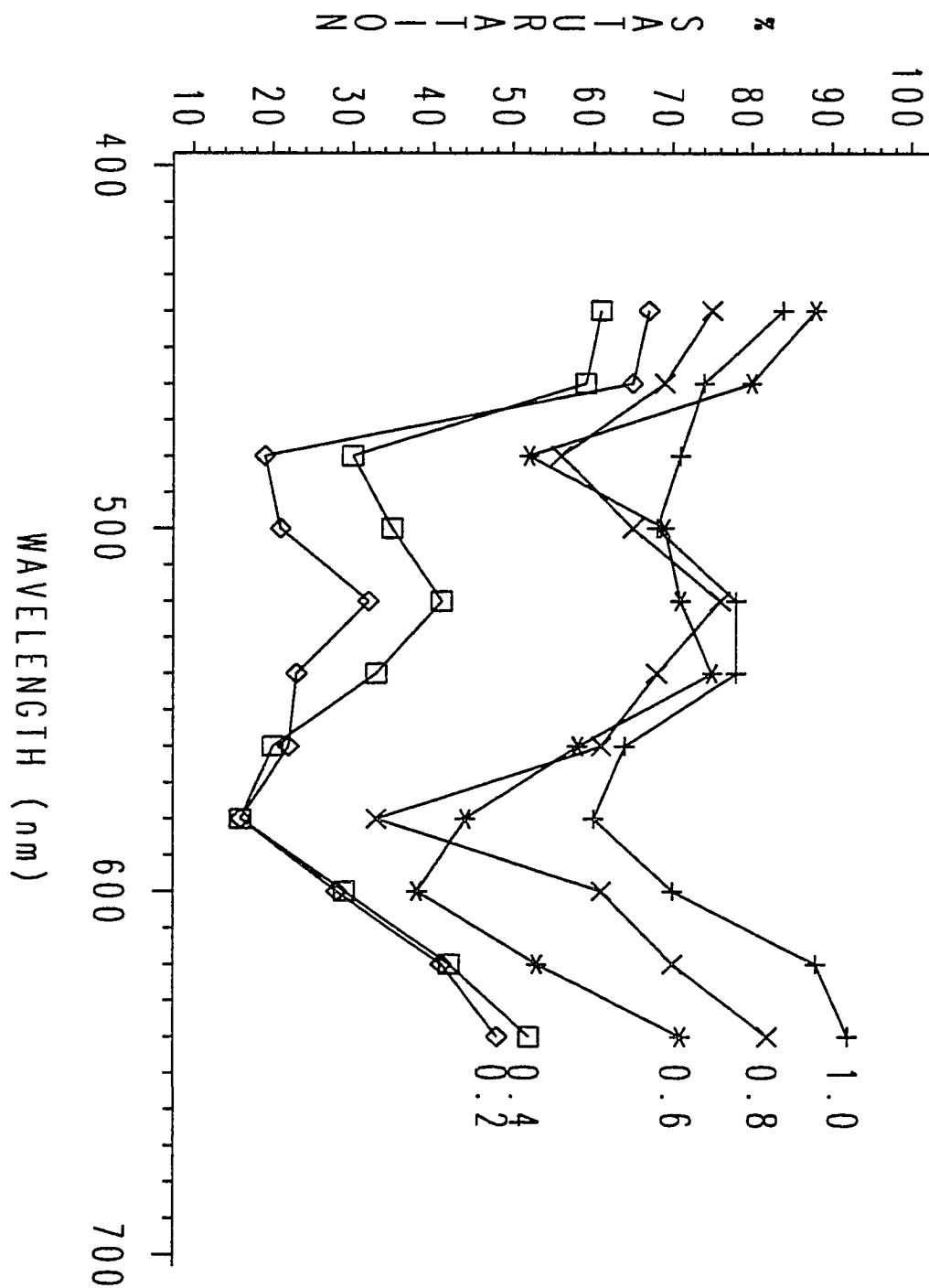


Figure 20. Percentage of saturation versus wavelength for the saturation estimation data of experiment 4 (solid line connects the mean and vertical lines are the ranges for each wavelength) and for predicted saturation (square) for purities of 1.0 (panel A), 0.80 (panel B), 0.60 (panel C), 0.40 (panel D) and 0.20 (panel E). Predicted saturation was computed from equation 4 according to the procedure described in the text. Observer is JH.

Figure 20.

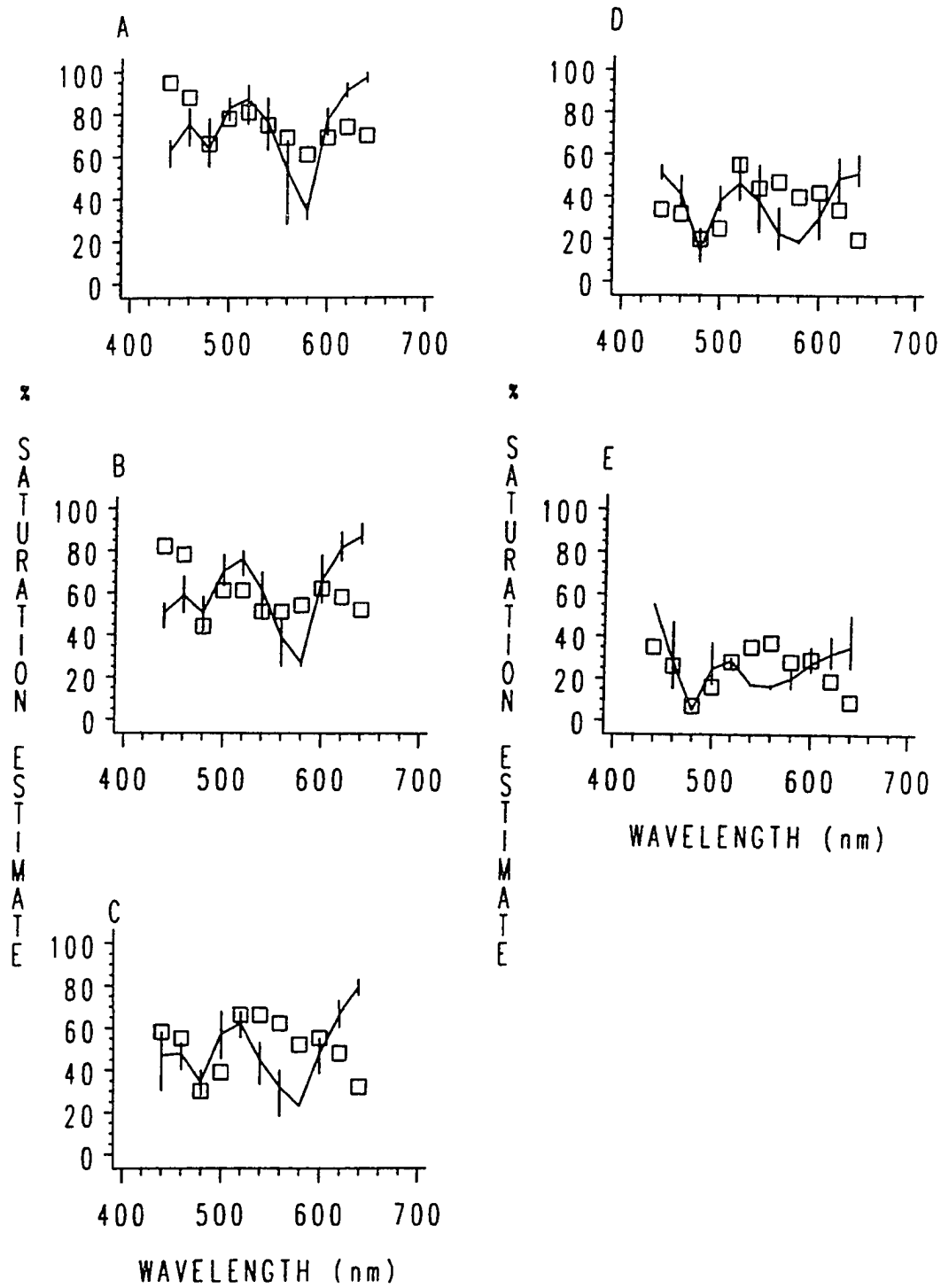


Figure 21. Same as Figure 20, for observer RS.

Figure 21.

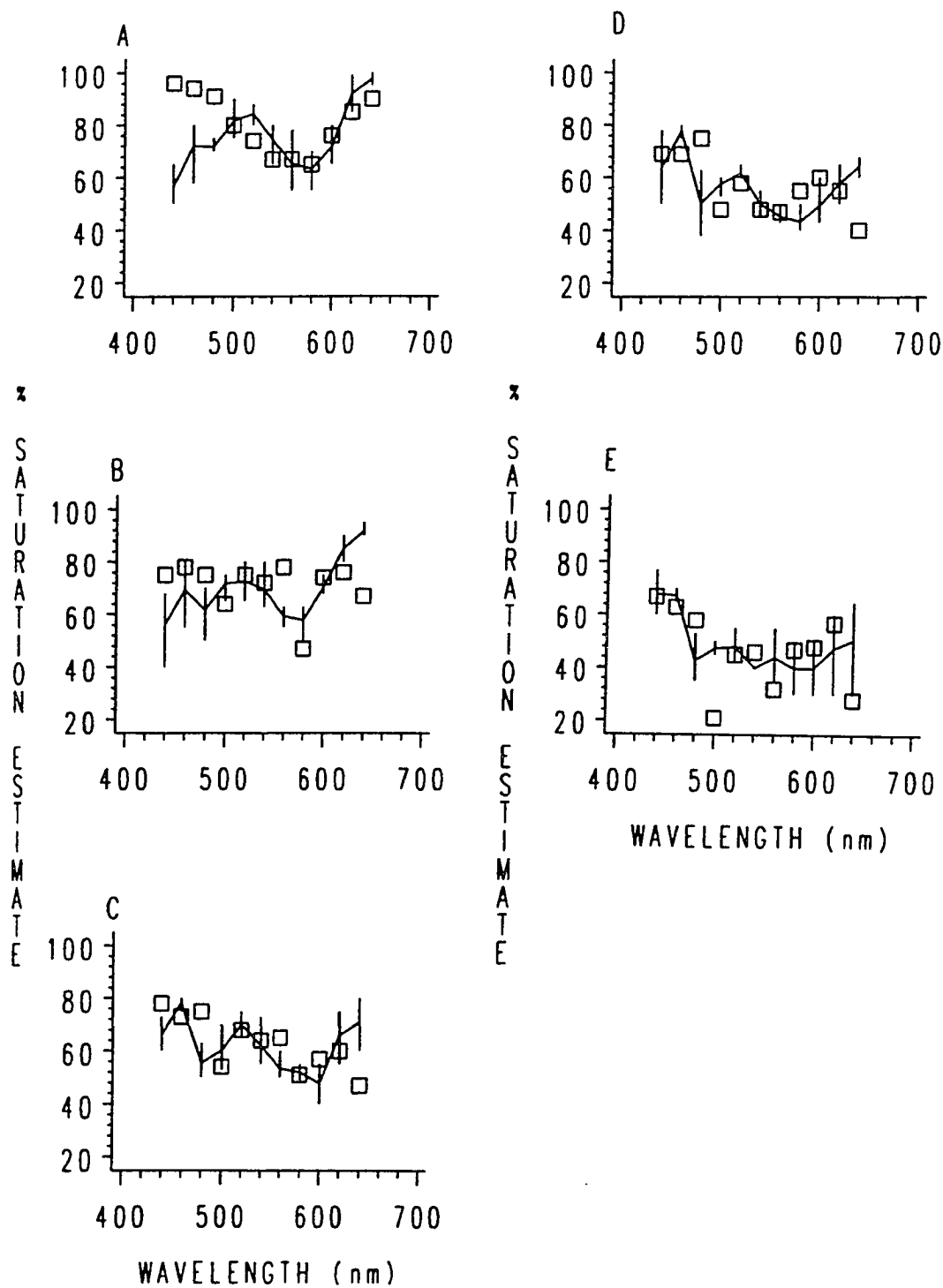


Figure 22. Same as Figure 20, for observer RH.

Figure 22.

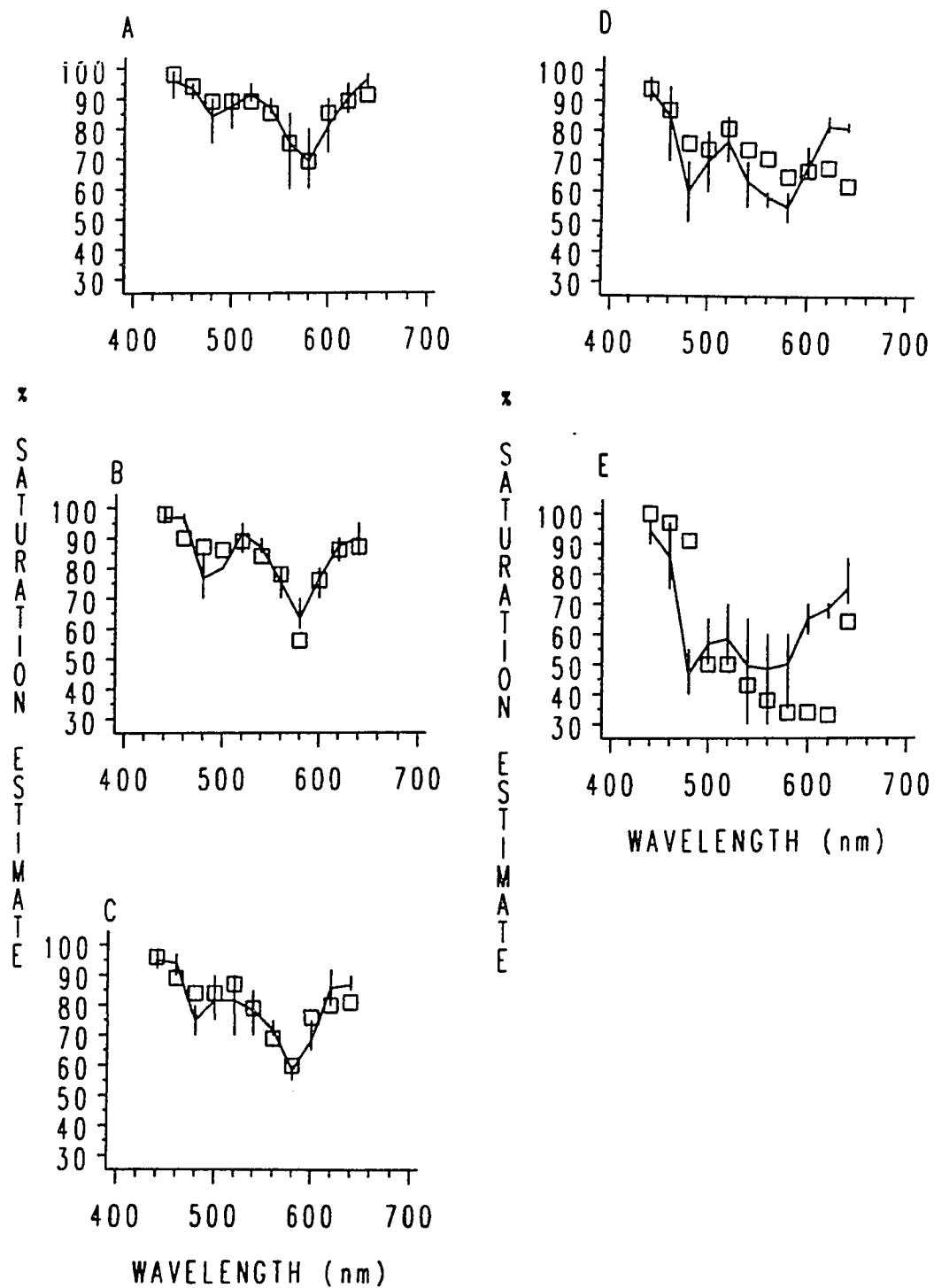


Figure 23. Same as Figure 20, for observer DM.

Figure 23.

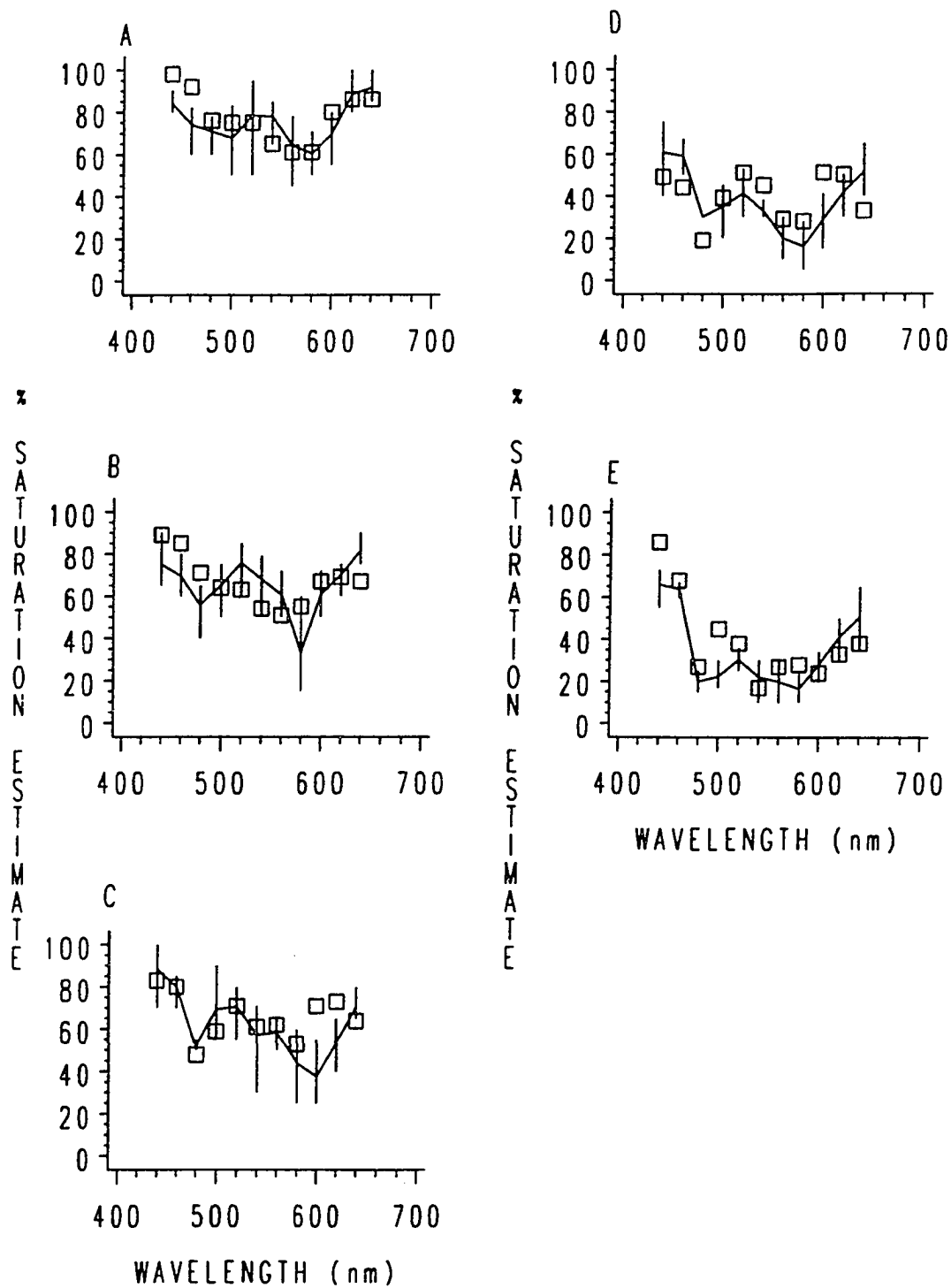


Figure 24. Difference between the saturation estimate and predicted saturation data of Figure 20 versus wavelength for purities of 1.0(*), 0.80(+), 0.60(X), 0.40 (square) and 0.20 (diamond). The different purities are displaced vertically for clarity.

Figure 24.

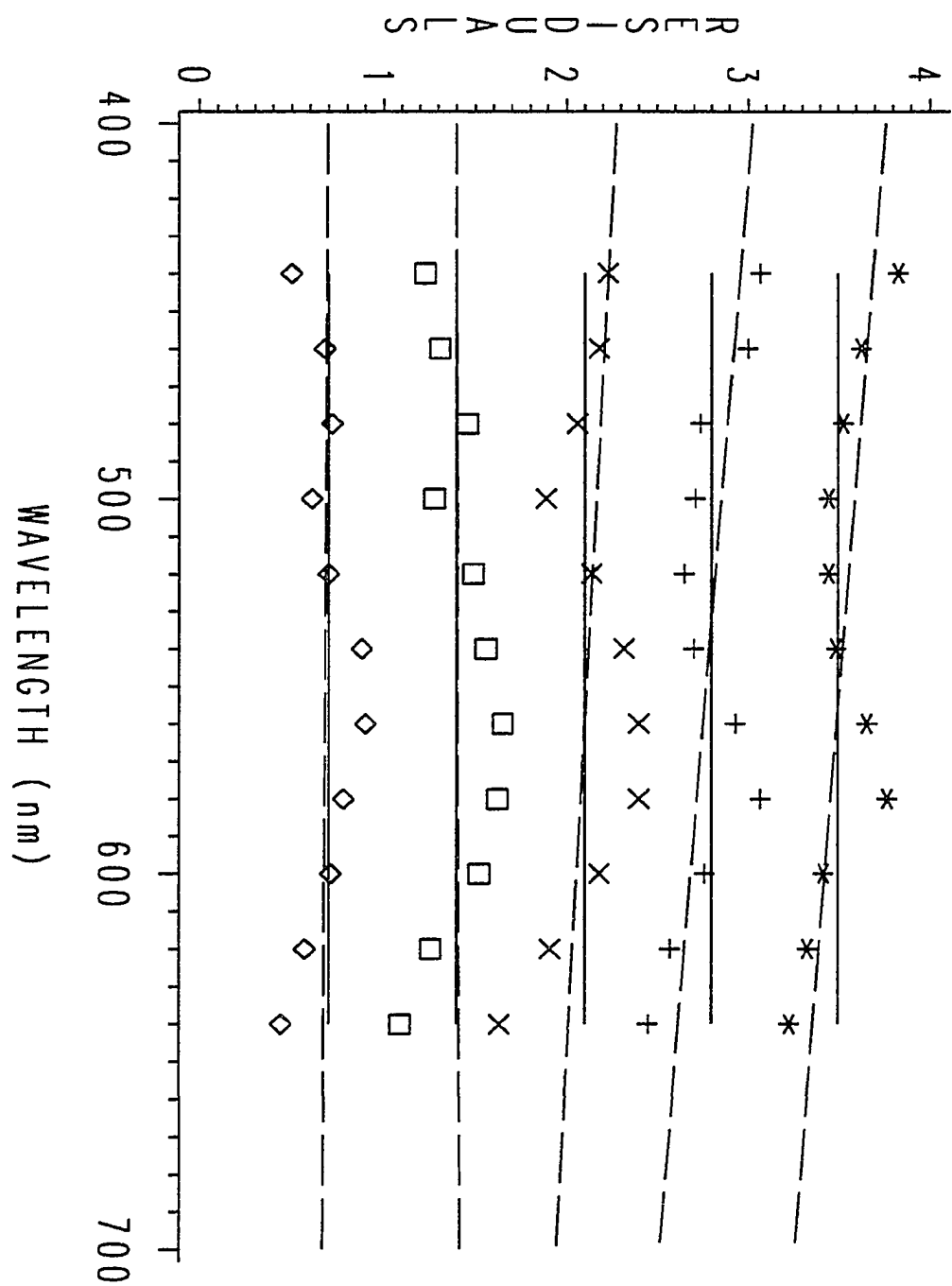


Figure 25. Same as Figure 25, for observer RS.

Figure 25.

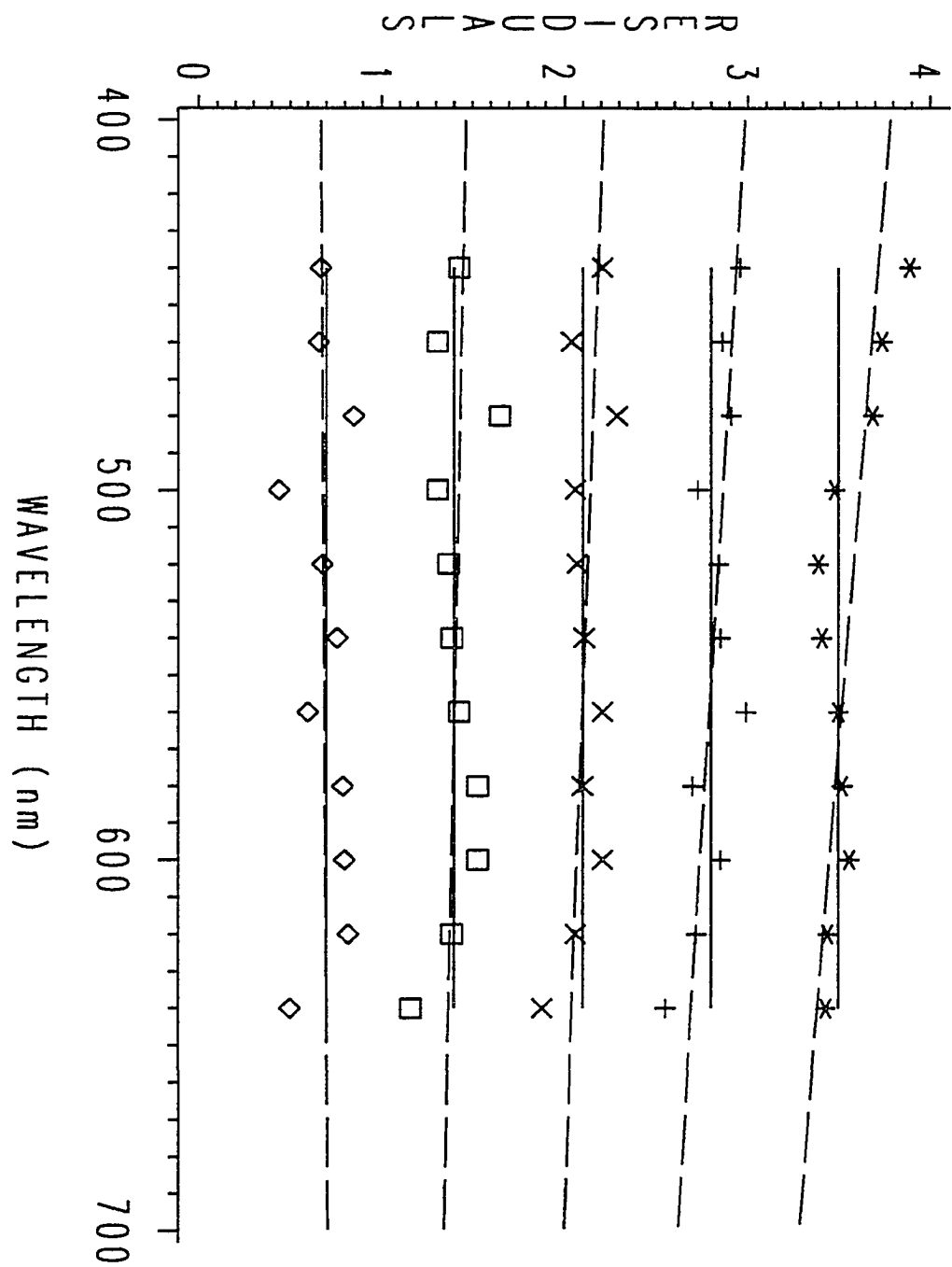


Figure 26. Same as Figure 25, for observer RH.

Figure 26.

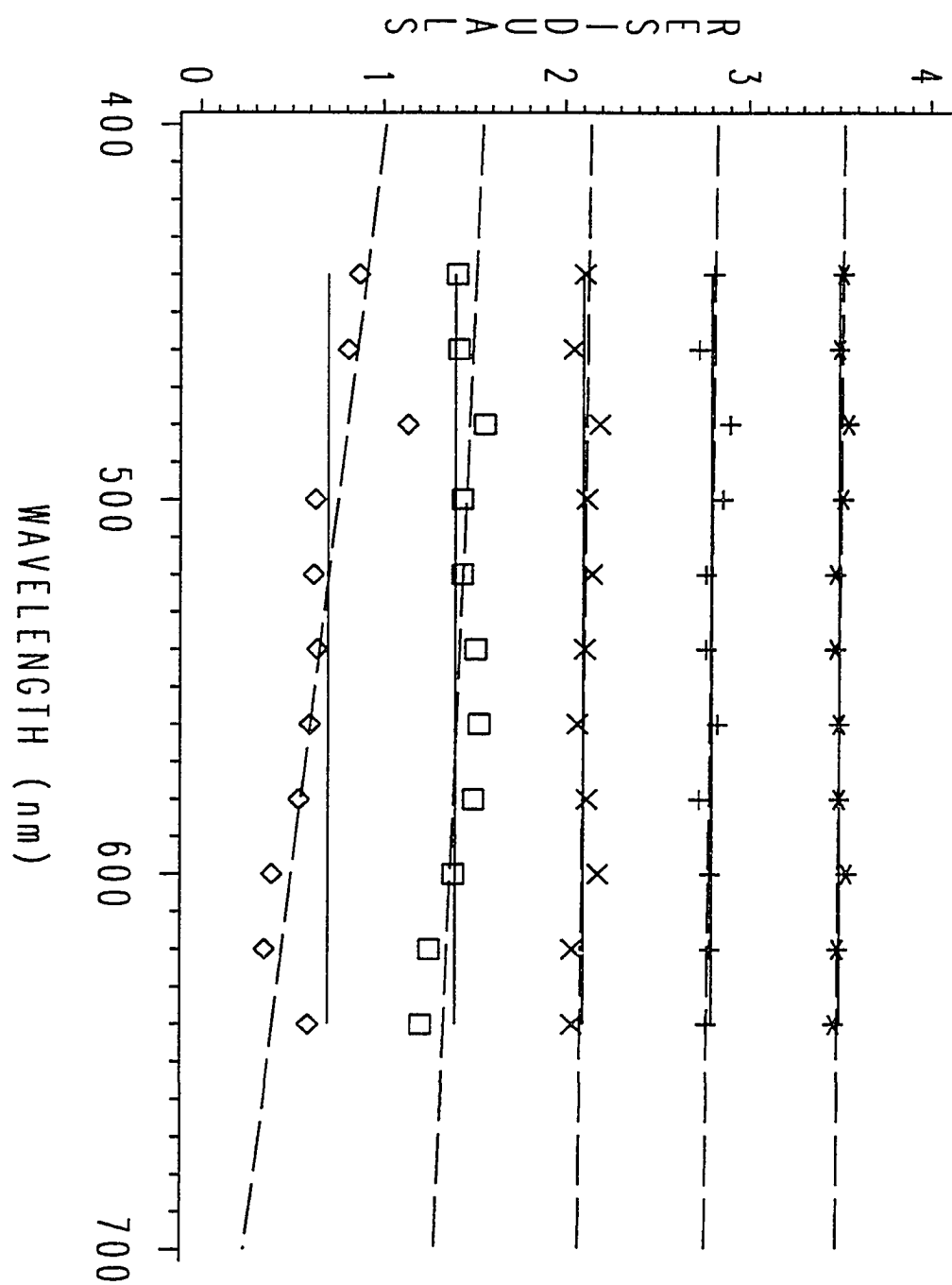


Figure 27. Same as Figure 25, for observer DM.

Figure 27.

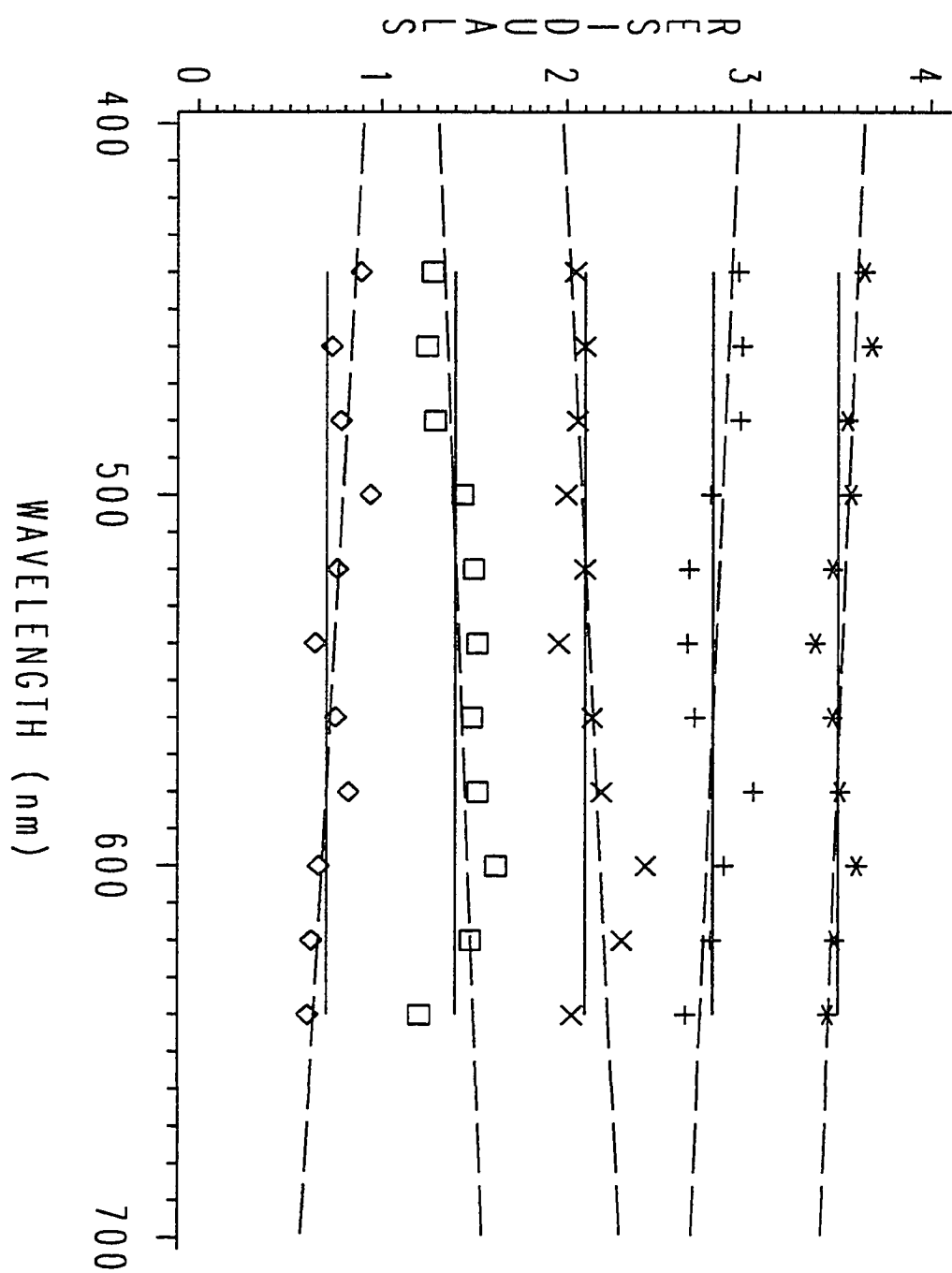


Figure 28. Percentage saturation estimate versus wavelength for purities of 0.80(+), 0.60(X), 0.40(*) and 0.20(square) for the blue light control condition. See text for details. Observer is JH.

Figure 28.

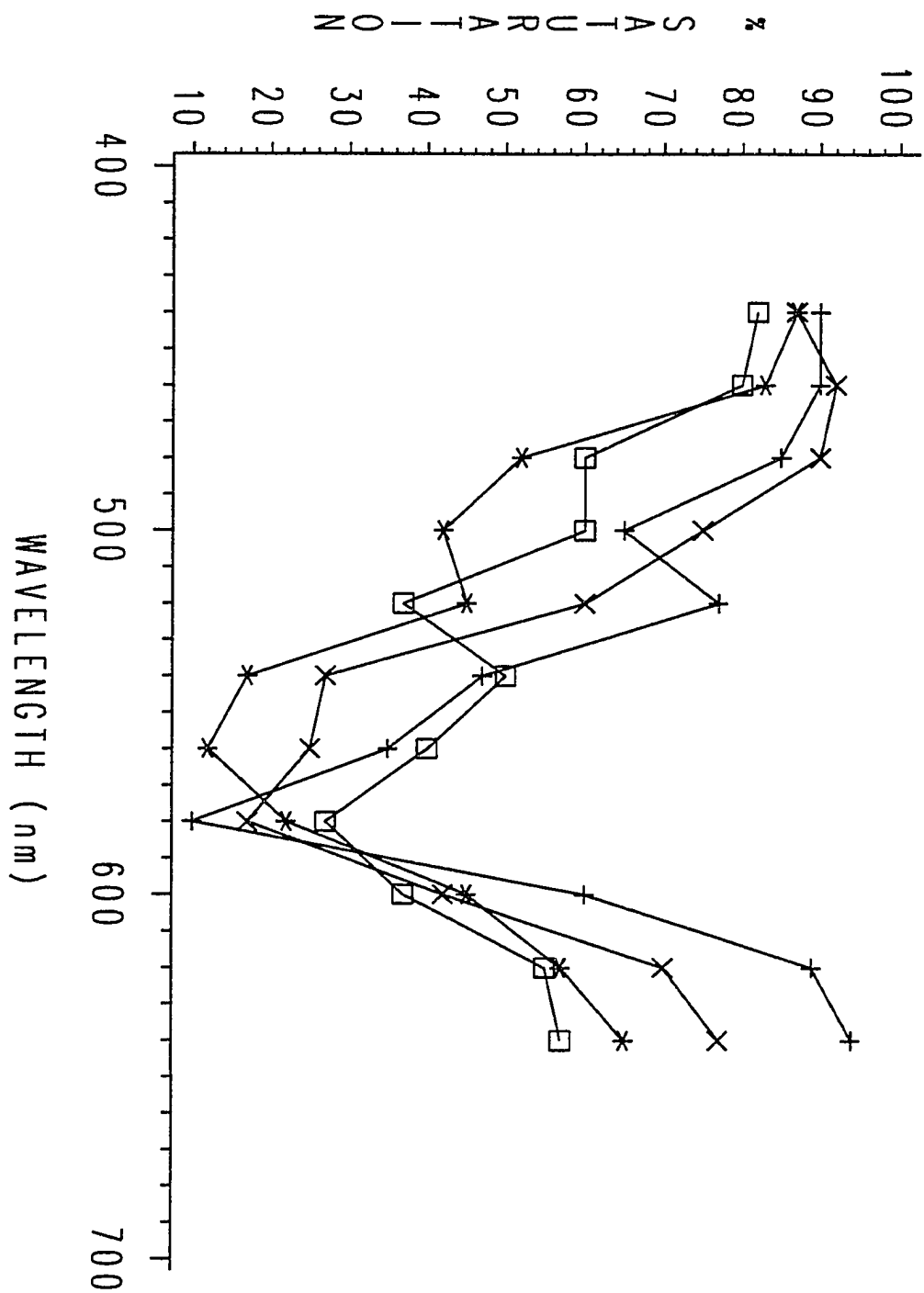


Figure 29. Relative chromatic response functions, yellow-blue(solid line) and red-green(interrupted line) measured by hue cancellation for rod control conditions A(+), B(X), C(*) and D (square). Each symbol represents the mean of two measurements. All curves are normalized to a chromatic response of 1.5 at 520nm on the green curve. Observer is JH.

Figure 29.

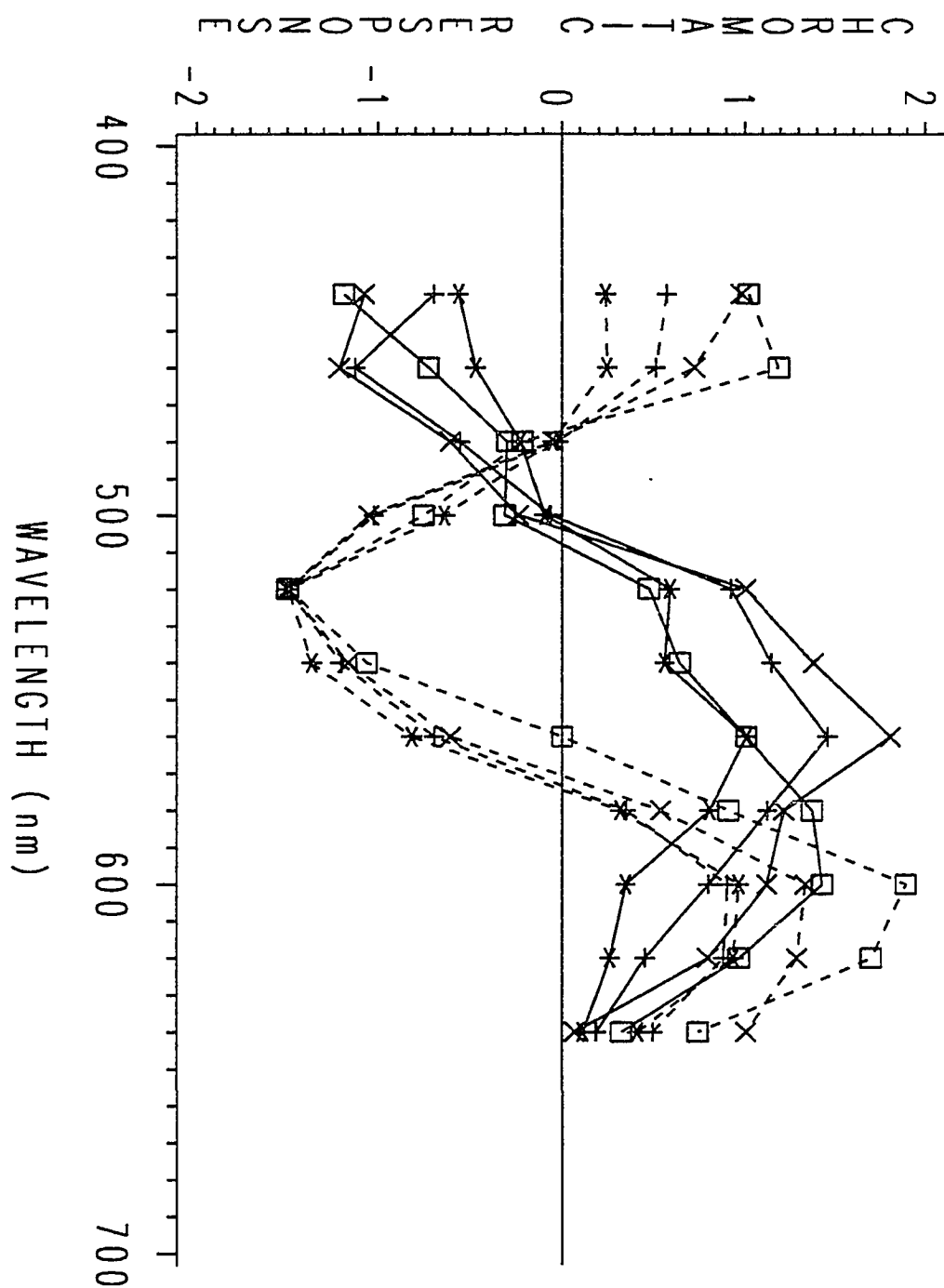


Figure 30. Percentage of hue versus wavelength for the hue naming data(solid line connects the mean and vertical lines are the ranges for each wavelength) and for predicted hue(square) for rod control conditions A(panel A), B(panel B), C(panel C), D(panel D). Predicted hue was computed from equations 2 and 3 and the chromatic response function for the respective condition. The percentage of red or green is plotted on the left vertical axis and the percentage of yellow or blue is plotted on the right vertical axis. Observer is JH.

Figure 30.

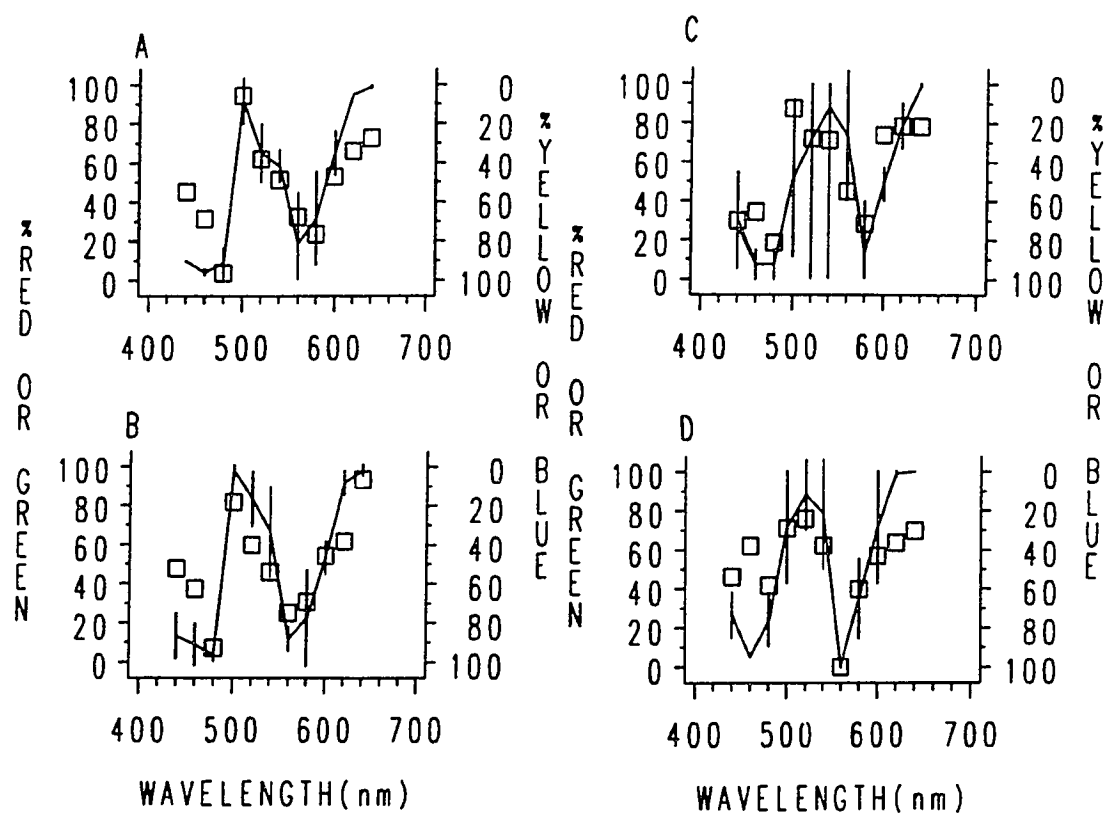


Figure 31. Achromatic response for rod control conditions A(*), B(+), C(X). Log relative sensitivity is plotted versus wavelength. All curves are normalized to 580nm. Judd's modified V_{λ} function(square) is plotted for comparison. Observer is JH.

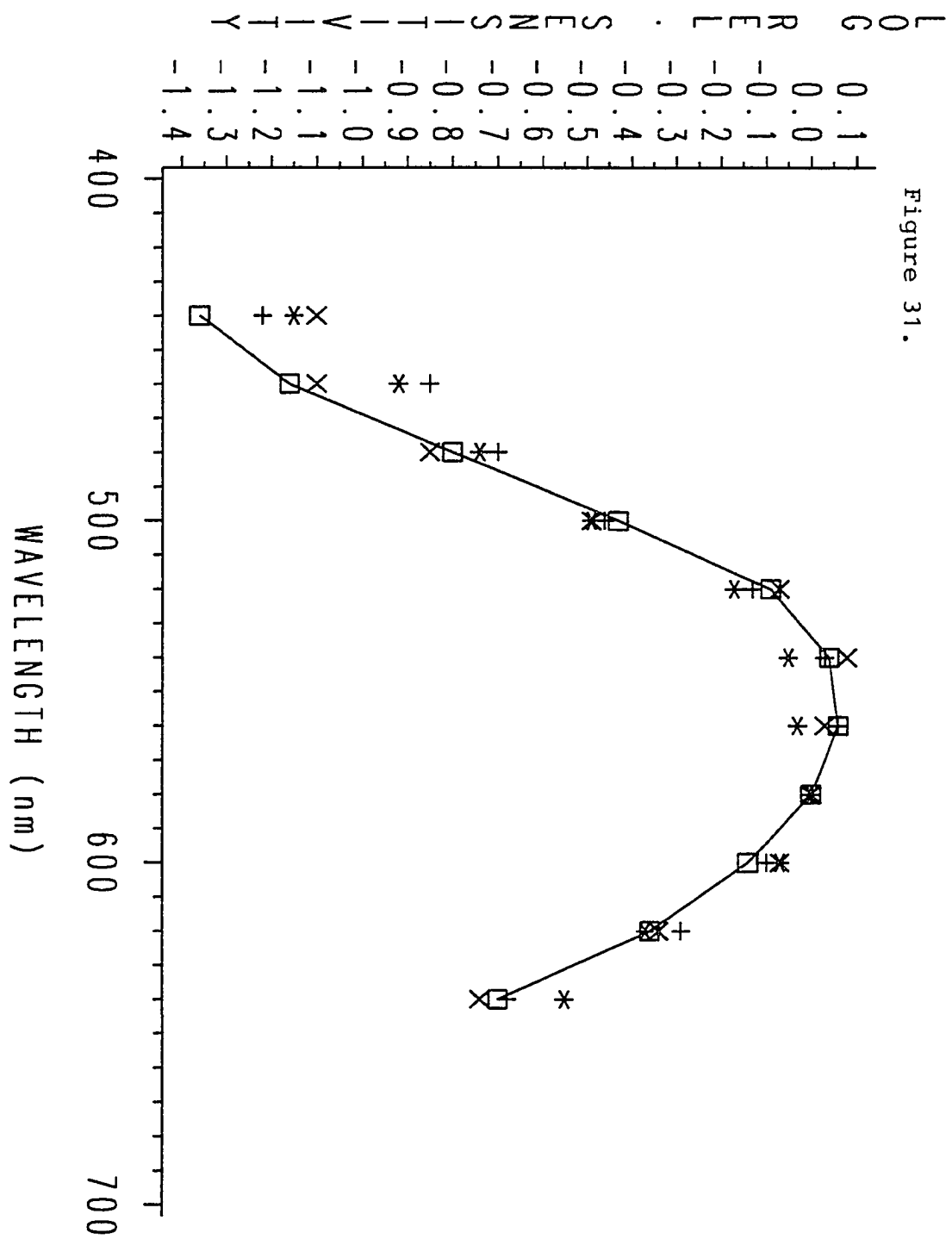


Figure 32. Percentage of saturation versus wavelength for rod control conditions A(plus), B(X), C(*) and D(square). Each point is the mean of three responses. Observer is JH.

Figure 32.

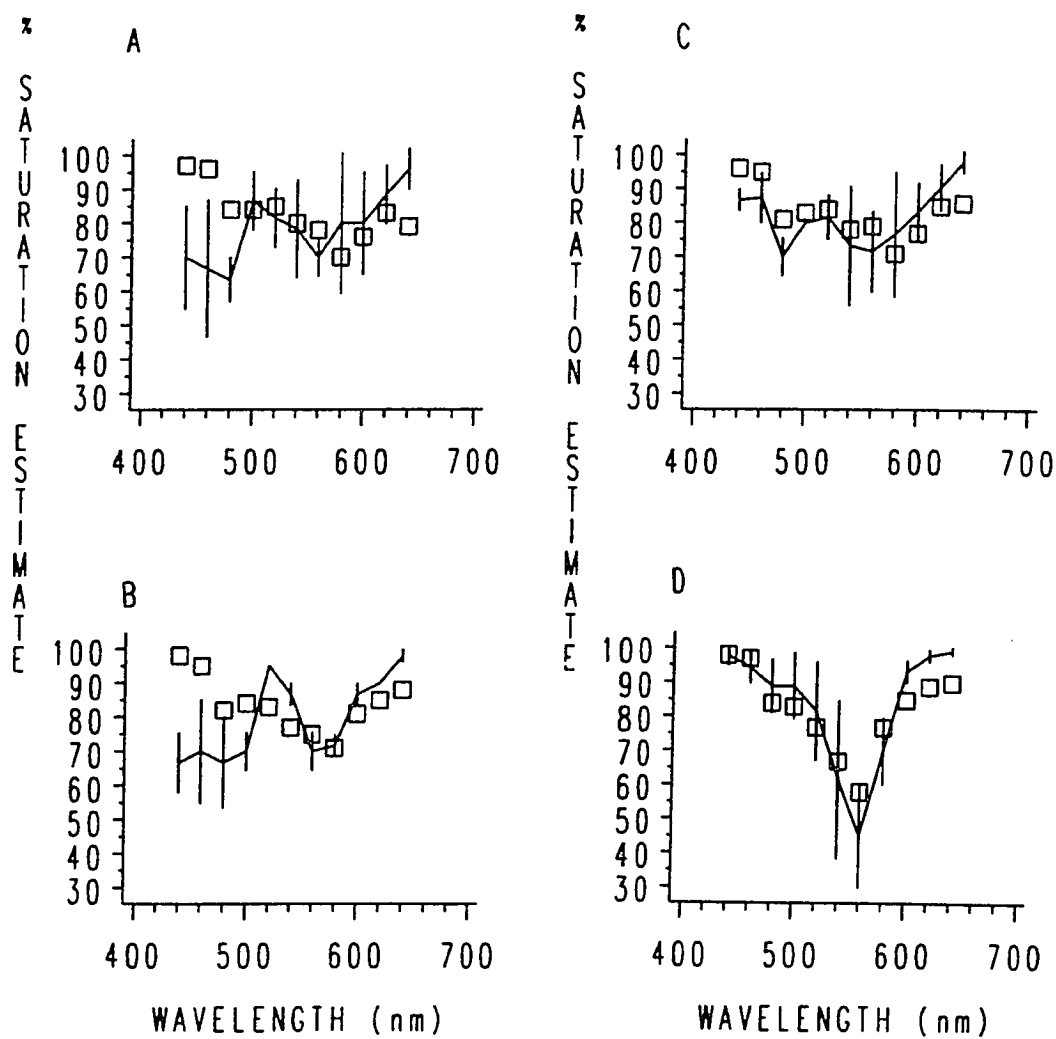


Figure 33. Percentage of saturation versus wavelength for the saturation estimation (solid line connects the mean and vertical lines are the ranges for each wavelength) and for predicted saturation (square) for rod control conditions A(panel A), B(panel B), C(panel C) and D(panel D). Predicted saturation was computed from equation 4 according to the procedure described in the text. Observer is JH.

Figure 33.

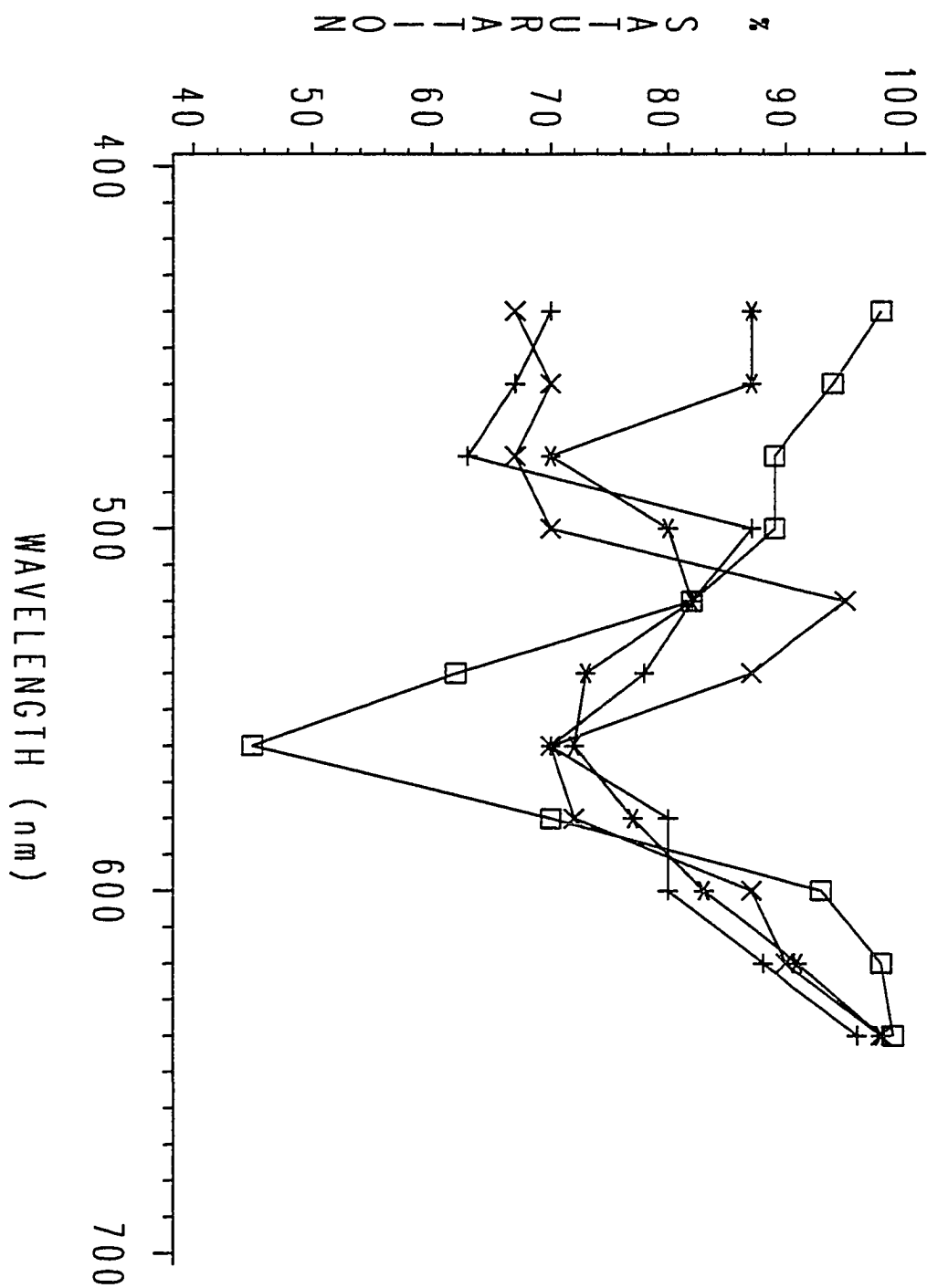
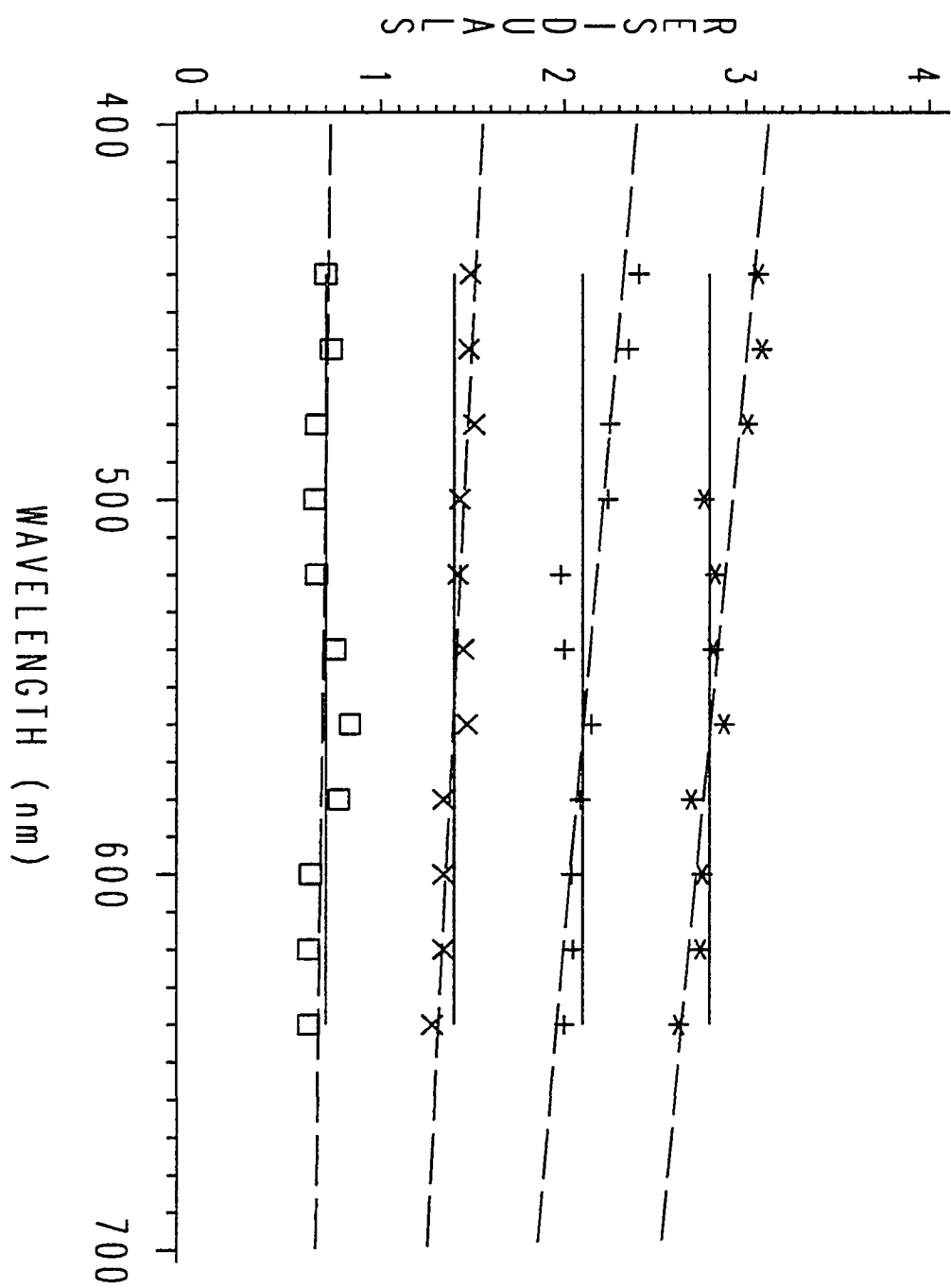


Figure 34. Difference between the saturation estimate and predicted saturation data of Figure 33 versus wavelength for rod control conditions A(*), B(+), C(X) and D(square). The different conditions are displaced vertically for clarity. Observer is JH.

Figure 34.



VII. TABLES

Table 1.
Wavelengths of Unique Hues

Subject	Yellow	Blue	Green
JH	577nm(2nm)	472nm(6nm)	504nm(4nm)
RS	580nm(10nm)	475nm(6nm)	490nm(2nm)
RH	571nm(4nm)	477nm(8nm)	492nm(2nm)
DM	578nm(2nm)	474nm(4nm)	528nm(18nm)

Table 2.
Subject-JH: Predicted/obtained hue for Pc=1.0 to Pc=0.20

Wave. (nm)	Hue	Pc=1.00	Pc=0.80	Pc=0.60	Pc=0.40	Pc=0.20
440	B-R	0.69	0.64	0.73	0.71	0.90
		0.95	0.85	0.68	0.50	0.37
460	B-R	0.71	0.84	0.74	0.71	0.86
		0.97	0.97	0.91	0.75	0.55
480	B-G	0.93	1.00	1.00	0.79B-GR	0.76B-GR
		0.93	0.95	0.99	0.97	0.86
500	B-G	0.04	0.05	0.03	0.06	0.43G-YB
		0.15	0.22	0.11	0.27	0.37
520	Y-G	0.43	0.24	0.48	0.63	0.68
		0.17	0.20	0.40	0.26	0.45
540	Y-G	0.40	0.40	0.57	0.55	0.73
		0.20	0.17	0.53	0.37	0.87
560	Y-G	0.56	0.67	0.70	0.82	0.90
		0.59	0.58	0.93	0.98	0.98
580	Y-R	0.81Y-RG	0.94	1.00	0.74	0.88Y-RG
		0.86	0.97	0.90	0.99	0.98
600	Y-R	0.38	0.47	0.58	0.55	0.67
		0.43	0.50	0.52	0.73	0.65
620	Y-R	0.19	0.21	0.34	0.33	0.53
		0.07	0.23	0.25	0.30	0.43
640	Y-R	0.14	0.15	0.20	0.25	0.44
		0.02	0.04	0.12	0.32	0.35

Table 3.
Subject-RS: Predicted/obtained hue for Pc=1.0 to Pc=0.20

Wave. (nm)	Hue	Pc=1.00	Pc=0.80	Pc=0.60	Pc=0.40	Pc=0.20
440	B-R	0.98 0.93	0.88 0.95	0.99 0.88	0.98 0.62	0.99 0.52
460	B-R	0.98 0.98	0.88 0.92	0.98 0.90	0.98 0.73	1.00 0.58
480	B-G	0.91 0.70	0.87 0.68	0.94 0.52	0.96B-GR 0.87	0.98B-GR 0.60
500	Y-G	0.24 0.23	0.03 0.07	0.56 0.65	0.48 0.48	0.71 0.88
520	Y-G	0.51 0.55	0.46 0.63	0.62 0.67	0.54 0.60	0.84 0.87
540	Y-G	0.59 0.73	0.59 0.67	0.71 0.78	0.58 0.73	0.87 0.93
560	Y-G	0.76 0.80	0.80 0.78	0.82 0.90	0.65 0.85	0.81 0.95
580	Y-RG	0.82Y-RG 0.86	0.79Y-RG 0.85	0.91Y-RG 0.87	0.94Y-RG 0.95	0.99Y-RG 0.94
600	Y-R	0.45 0.67	0.44 0.40	0.56 0.63	0.68 0.85	0.92 0.88
620	Y-R	0.29 0.02	0.28 0.20	0.48 0.40	0.57 0.33	0.93 0.83
640	Y-R	0.24 0.00	0.25 0.00	0.45 0.33	0.50 0.22	0.86 0.47

Table 4.
Subject-RH: Predicted/obtained hue for Pc=1.0 to Pc=0.20

Wave. (nm)	Hue	Pc=1.00	Pc=0.80	Pc=0.60	Pc=0.40	Pc=0.20
440	B-R	0.84	0.83	0.74	0.94	0.99
		0.85	0.68	0.62	0.70	0.60
460	B-R	0.83	0.66	0.76	0.97	0.98
		0.95	0.80	0.72	0.62	0.58
480	B-G	0.81	0.77	0.92	0.95	0.98B-GR
		0.87	0.92	0.83	0.60	0.57
500	Y-G	0.12	0.25	0.15	0.52	0.64
		0.28	0.15	0.18	0.33	0.97
520	Y-G	0.18	0.35	0.20	0.55	0.70
		0.28	0.23	0.40	0.63	0.72
540	Y-G	0.30	0.39	0.32	0.57	0.74
		0.37	0.32	0.55	0.83	0.86
560	Y-G	0.51Y-RG	0.54	0.57	0.60Y-GR	0.84Y-GR
		0.80	0.51	0.71	0.88	0.92
580	Y-R	0.61	0.49	0.78	0.65	0.88
		0.60	0.80	0.82	0.92	0.78
600	Y-R	0.35	0.04	0.54	0.69	0.55
		0.17	0.42	0.58	0.60	0.50
620	Y-R	0.26	0.24	0.45	0.51	0.50
		0.00	0.08	0.25	0.35	0.38
640	Y-R	0.32	0.23	0.35	0.53	0.50
		0.07	0.03	0.12	0.25	0.32

Table 5.
Subject-DM: Predicted/obtained hue for Pc=1.0 to Pc=0.20

Wave. (nm)	Hue	Pc=1.00	Pc=0.80	Pc=0.60	Pc=0.40	Pc=0.20
440	B-R	0.74	0.72	0.69	0.58	0.58
		0.88	0.83	0.67	0.55	0.53
460	B-R	0.71	0.83	0.79	0.64	0.64
		0.90	0.87	0.82	0.60	0.52
480	B-G	0.79	0.91	0.92	0.87B-RG	0.65B-RG
		0.83	0.80	0.57	0.77	0.78
500	B-G	0.42	0.29	0.29Y-RG	0.32	0.11Y-RG
		0.18	0.32	0.13	0.23	0.23
520	Y-G	0.21	0.26	0.21	0.10	0.13
		0.25	0.37	0.40	0.27	0.40
540	Y-G	0.28	0.35	0.27	0.31	0.43
		0.23	0.28	0.40	0.27	0.33
560	Y-G	0.60	0.68	0.80	0.53	0.56
		0.40	0.47	0.50	0.57	0.63
580	Y-RG	1.00Y-RG	0.98Y-RG	1.00Y-RG	1.00Y-RG	0.49Y-RG
		0.80	0.67	0.70	0.57	0.18
600	Y-R	0.26	0.43	0.40	0.22	0.20
		0.43	0.47	0.35	0.27	0.32
620	Y-R	0.17	0.17	0.26	0.19	0.09
		0.23	0.23	0.18	0.27	0.23
640	Y-R	0.09	0.08	0.19	0.07	0.09
		0.00	0.08	0.10	0.13	0.30

Table 6.
Slope of linear regression equation: Hue versus purity.

Wave.	Subject-JH		Subject-RS		Subject-RH		Subject-DM	
	Pred.	Obt.	Pred.	Obt.	Pred.	Obt.	Pred.	Obt.
440	-0.26	+0.76	-0.06	+0.58	-0.21	+0.24	+0.23	+0.49
460	-0.10	+0.53	-0.07	+0.50	-0.31	+0.46	+0.17	+0.52
480	+0.28	+0.06	-0.12	+0.01	-0.26	+0.46	+0.16	+0.07
500	-0.40	-0.25	-0.70	-0.86	-0.66	-0.78	+0.30	-0.01
520	-0.45	-0.31	-0.37	-0.31	-0.62	-0.64	+0.16	-0.10
540	-0.41	-0.77	-0.28	-0.23	-0.53	-0.75	-0.13	-0.10
560	-0.42	-0.59	+0.03	-0.19	-0.36	-0.31	+0.12	-0.28
580	+0.03	-0.13	-0.25	-0.13	-0.35	-0.24	+0.50	+0.67
600	-0.33	-0.34	-0.59	-0.44	-0.53	-0.42	+0.17	+0.21
620	-0.40	-0.40	-0.79	-0.88	-0.38	-0.52	+0.07	-0.02
640	-0.36	-0.47	-0.75	-0.58	-0.33	-0.36	+0.01	-0.33

Table 7.
Predicted versus obtained hue (%) for Pc=1.0 to Pc=0.20

Observer	Purity	Mean difference	Correlation(P value)
JH	1.00	13.3	0.91(0.000)
	0.80	10.1	0.93(0.000)
	0.60	9.0	0.94(0.000)
	0.40	17.1	0.75(0.007)
	0.20	16.0	0.60(0.053)
RS	1.00	11.5	0.90(0.000)
	0.80	9.5	0.93(0.000)
	0.60	11.0	0.74(0.001)
	0.40	16.5	0.61(0.048)
	0.20	20.4	-0.43(0.188)
RH	1.00	13.7	0.87(0.000)
	0.80	16.4	0.77(0.005)
	0.60	12.4	0.82(0.002)
	0.40	23.2	0.26(0.435)
	0.20	20.0	0.33(0.329)
DM	1.00	12.9	0.88(0.000)
	0.80	9.9	0.91(0.000)
	0.60	15.5	0.83(0.002)
	0.40	10.3	0.90(0.000)
	0.20	14.9	0.70(0.017)

Table 8.
Predicted versus obtained saturation (%) for linear
valence model(LVM) versus nonlinear, rod model(NLRM).

Obs.	Purity	Mean Difference		Correlation(P value)	
		LVM	NLRM	LVM	NLRM
JH	1.00	14.1	11.9	.28(.404)	.74(.009)
	0.80	17.2	9.4	.09(.794)	.66(.028)
	0.60	18.7	8.8	-.27(.417)	.72(.011)
	0.40	15.7	7.1	-.07(.829)	.76(.006)
	0.20	10.8	2.7	.23(.501)	.96(.000)
RS	1.00	11.4	8.8	.10(.772)	.32(.331)
	0.80	10.5	8.0	.16(.641)	.53(.088)
	0.60	8.4	4.8	.36(.284)	.72(.013)
	0.40	9.5	4.3	.27(.421)	.84(.001)
	0.20	10.6	3.0	.49(.129)	.95(.000)
RH	1.00	1.9	3.9	.95(.000)	.76(.007)
	0.80	4.0	5.8	.88(.000)	.72(.013)
	0.60	4.4	6.3	.88(.000)	.78(.005)
	0.40	8.6	6.4	.54(.084)	.70(.016)
	0.20	17.9	7.2	.54(.086)	.78(.005)
DM	1.00	7.3	3.9	.67(.024)	.76(.007)
	0.80	11.5	5.8	.41(.215)	.71(.013)
	0.60	9.6	6.3	.51(.113)	.78(.005)
	0.40	12.2	6.4	.48(.139)	.70(.016)
	0.20	9.8	7.2	.83(.001)	.78(.005)

Table 9.

Rod Control Condition Results

Condition	A	B	C	D
Stimulus Parameters:				
Presentation Time 1 (sec.)		2	1	0.09
Field Size(deg)	2.6	2.6	0.60	0.60
Mean range:				
Hue Naming	16.3	17.4	33.9	23.2
Saturation Est.	20.0	8.9	13.5	13.8
Predicted/Obtained				
Hue:				
Pearson r	0.854	0.875	0.851	0.730
(p value)	0.0008	0.0004	0.0009	0.0108
Mean Abs. Diff.	15.2	17.1	16.4	19.1
Predicted/Obtained				
Saturation:				
Pearson r	-0.406	-0.081	0.554	0.939
(p value)	0.2156	0.8128	0.0770	0.0001
Mean Abs. Diff.	11.7	12.5	6.8	6.4
Slope of Residuals				
Verses Wavelength	-0.002	-0.001	-0.001	-0.000

Table 10.
Rod Control Conditions: Predicted/Obtained Hue

Wave- length	Hue	Condition A		Condition B		Condition C		ConditionD	
		Pred.	Obt.	Pred.	Obt.	Pred.	Obt.	Pred.	Obt.
440	B-R	0.55	0.90	0.52	0.87	0.70	0.73	0.54	0.73
460	B-R	0.69	0.96	0.62	0.91	0.66	0.93	0.38	0.95
480	B-G	0.96	0.91	0.92	0.97	0.82	0.93	0.58	0.77
500	B-G	0.06	0.08	0.18	0.02	0.13	0.25	0.29	0.28
520	Y-G	0.38	0.35	0.40	0.17	0.28	0.08	0.24	0.12
540	Y-G	0.49	0.42	0.54	0.33	0.29	0.12	0.38	0.22
560	Y-G	0.68	0.82	0.74	0.88	0.55	0.27	1.00	0.99
580	Y-R	0.76	0.68	0.69	0.78	0.72	0.87	0.60	0.65
600	Y-R	0.46	0.35	0.45	0.47	0.26	0.52	0.43	0.28
620	Y-R	0.34	0.05	0.38	0.08	0.22	0.22	0.36	0.01
640	Y-R	0.27	0.01	0.06	0.02	0.22	0.01	0.30	0.00

Table 11.
Rod Control Conditions: Predicted/Obtained Saturation

Wave-length	Condition A		Condition B		Condition C		ConditionD	
	Pred.	Obt.	Pred.	Obt.	Pred.	Obt.	Pred.	Obt.
440	0.97	0.70	0.98	0.67	0.96	0.87	0.98	0.98
460	0.96	0.67	0.95	0.70	0.95	0.87	0.97	0.94
480	0.84	0.63	0.80	0.67	0.81	0.70	0.84	0.89
500	0.84	0.87	0.82	0.70	0.83	0.80	0.83	0.89
520	0.85	0.82	0.81	0.95	0.84	0.82	0.77	0.82
540	0.80	0.78	0.75	0.87	0.78	0.73	0.67	0.62
560	0.78	0.70	0.72	0.70	0.79	0.72	0.58	0.45
580	0.70	0.80	0.69	0.72	0.71	0.77	0.77	0.70
600	0.76	0.80	0.79	0.87	0.77	0.83	0.85	0.93
620	0.83	0.88	0.84	0.90	0.85	0.91	0.89	0.98
640	0.79	0.96	0.87	0.98	0.86	0.98	0.90	0.99

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